A N N U A L R E P O R T

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U. S. WATER CONSERVATION LABORATORY
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TITLE: GERMPLASM DEVELOPMENT AND DOMESTICATION OF CUPHEA AND OTHER NEW CROP SPECIES

STRATEGIC PLAN: 2.1.03.1.a   CRIS WORK UNIT: 5422-20080-001

INTRODUCTION

Numerous studies have identified the need and potential of new or alternate crops research. High yields of traditional crops in the arid Southwest depend upon extensive irrigation. New crops with low water use will be needed if agriculture is to persist in the region.

The U.S. chemical industry is heavily dependent upon imported coconut and palm kernel oils as the primary source of lauric acid for manufacturing soaps, detergents, lubricants, and other related products. Seed oils from species of *Cuphea* contain high levels of lauric and other medium-chain fatty acids. Seed dormancy, seed shattering, sticky glandular hairs, and indeterminate patterns of growth and flowering are major constraints to domestication.

The U.S. is also dependent upon imported castor oil for its total supply of hydroxylated fatty acid, a strategic material used for the production of lubricants, plasticizers, protective coatings, surfactants, and pharmaceuticals. High seed toxicity and allergenic reactions from plants limit production of castor beans in the U. S. Seed oils from species of *Lesquerella*, many of which are adapted to arid lands, contain sizable quantities of 3 hydroxy fatty acids. Domestication of adapted species appears feasible.

PROCEDURE

The planned transfer of the USDA/ARS cuphea germplasm collection to the North Central Plant Introduction Station at Ames, IA, to provide better facilities for maintenance, increase, and distribution was completed during the year. Transfer of responsibility and funding for the specific cooperative agreement (58-9AHZ-3-744) at Oregon State University was made at the end of FY 86. Management of this phase of the program now also resides at Ames, IA. Results of the research conducted in Oregon under the specific cooperative agreement are presented in a separate report (CRIS No. 5422-20160-004-01). Research conducted under a broad-form cooperative agreement at the Arizona AES (58-9AHZ-3-38) on interspecific hybridization and cytogenetics of cuphea was terminated at the end of FY 86 due to insufficient funds.

Research on cuphea concentrates on germplasm enhancement through both intra- and interspecific hybridization. The primary objective is to obtain new genetic recombinations leading to removal of major constraints to domestication and productivity. Segregating material and improved germplasm are provided to cooperating scientists for evaluation in Oregon, Iowa, and Georgia.

Research on lesquerella concentrates on development of improved germplasm utilizing conventional plant breeding and genetic methods. Cooperative research on determination of water requirements and other crop management factors is conducted with other scientists in the Arid Zone Crop Research Unit of the U.S. Water Conservation Laboratory.

RESULTS AND DISCUSSION

Additional interspecific hybrids were made at Phoenix and Tucson. Various populations of new F_1's, F_2's and several backcrosses were grown in the greenhouse for evaluation and further crossing. Segregating F_2 populations of the fertile hybrid between the herbaceous annual _C. procumbens_ (n=9) and the perennial species _C. llavea_ (n=9) were grown at Ames, IA, Tifton, GA, and Corvallis, OR. The planting in Oregon was direct seeded and had to be replanted. No seeds were harvested from this planting since flowering was delayed. Significant plant-to-plant variation was observed at each location. Plant vigor of these hybrid plants was rated superior. Single plant selections and bulk F_2 seed harvests were made in Iowa and Georgia for further evaluation.

The first interspecific hybrid between the capric acid (C10:0) producing species _C. leptopoda_ (n=10) and the lauric acid producing _C. laminuligera_ (n=10) was verified cytologically. This combination may provide valuable information on the genetic control of fatty acid biosynthesis. The two species are also among the five most promising species agronomically. Irregular chromosome pairing with a high number of univalents contributes to the high degree of sterility. A series of experiments were conducted to develop a method using colchicine for doubling the chromosome number to induce amphidiploidy and restore fertility. Various combinations of colchicine concentration, and the use of vacuum infiltration and DMSO to improve penetration were tried. Relatively high mortality rates were experienced and little success has yet been obtained. Numberous unsuccessful attempts were also made to obtain viable seed by self pollination and backcrossing to the parental species. Additional research is needed to develop methodology for restoring fertility to allow release of genetic variability in several sterile hybrid species combinations.

Additional interspecific hybrids have been cytologically verified including: _C. procumbens_ (n=9) x _C. leptopoda_ (n=10), _C. procumbens_ (=9) x _C. crassiflora_ (n=12), _C. lanceolata_ (n=6) x _C. llavea_ (n=9), _C. procumbens_ (n=9) x _C. lanceolata_ (n=6), and 6 different combinations of _C. procumbens_ (n=9) x _C. llavea_ (n=9). All of the procumbens x llavea hybrids are relatively fertile and produce seed by self or cross pollination. Several backcrosses of F_1's with the 2 parental species have been made and are being evaluated.

When cuphea seed is harvested, a wide array of seed maturity is usually observed. A major contributing factor is indeterminate flowering and plant growth found in most species. If seed maturity markedly affects oil percentage and fatty acid content and distribution, such variation would have important consequences in regard to oil yield and quality.

It could also impact cultural, harvesting, and processing methodology, and could be an important factor in the breeding program for the development of improved, high yielding cultivars. To determine if seed maturity is a significant factor, an experiment was designed and conducted. Seed lots of eight Cuphea species were divided into two maturity classes, designated green and mature. In total, 80 -- 8 gram seed samples were prepared and sent to Dr. Robert Kleiman, NRRC, Peoria, IL, for analysis (Table 1). Correlations among seed characteristics of 11 seed maturity pairs of Cuphea wrightii seed lots (Table 1) were calculated (Table 2). Regressions were calculated and plotted for the two highly significant relationships: 1000 seed weight and seed maturity score (Fig. 1); and lauric acid % and capric acid % (Fig. 2). The 1000 seed weights of green or less mature seeds were significantly lighter than comparable mature seeds. However, oil percentage in the two maturity classes was essentially the same for all species. The mature seed lots of species that produce C12:0 (lauric acid) as the predominant fatty acid, had a slightly higher quantity of C12:0 and slightly lower quantity of C10:0 than that found in the green seed lots. This slight difference is not judged to be of practical significance. It is concluded that deposition of oil in cuphea seeds occurs very rapidly before seeds reach full maturity. Fatty acid distribution is apparently modified only slightly by seed maturity. It is further concluded that harvesting seed over a wide range of maturity is feasible and should increase total oil yields without significant adverse effects on oil quality.

An essentially unselected bulk seed lot of Lesquerella fendleri was used to determine the effect of plant population density on seed yield in a replicated experiment. Seed yields increased linearly in plots varying from approximately 100,000 to over 1.1 million plants/ha (Table 3). The highest yielding plots were those of the highest plant population, and averaged over 1360 kg/ha of cleaned seed. Plant height and width also increased with increasing plant population. Single plots (6 meter, double row on 1 meter wide raised vegetable beds) of half-sib families from 46 open pollinated single plant selections were also evaluated for yield and plant characteristics. The 10 best half-sib families averaged 1573 kg/ha of cleaned seed and the highest produced at the rate of 1740 kg/ha (Table 3).

A Hege plot combine was used in June to make a bulk harvest of plants left after the plant population study and the breeding plots were hand harvested. The combine was not equipped with the proper screens to efficiently handle the small sized seeds, and considerable seed was lost in the process. However, over 100 kg of cleaned seed were obtained and are now available for laboratory-pilot plant studies on methods of extraction, etc.

A planting of lesquerella was made in October to initiate a study on water usage. Concurrently, a planting of the 10 best half-sib families from single plant selections and a breeding nursery containing other selected germplasm was also planted. The planting was made on the flat instead of on raised beds, and flood irrigated instead of sprinkled.

This was a mistake, since we had significant soil crusting preventing seedling emergence. We also experienced some apparent damping off and some flea beetle injury. The two borders for the irrigation treatment were replanted in December and a good plant stand was obtained. Hopefully the delayed planting will not adversely affect the results on determination of soil moisture requirement. The seed for this planting was from a newly created 1986 Select Bulk utilizing equal aliquots of seed from the 10 best half-sib families. Four replications and four levels of irrigation will be used, based upon amount of soil water depletion monitored by neutron probes.

A preliminary evaluation was made on the growth and adaptation of *Vernonia galamensis*, a new plant source of vernolic (epoxy) acid. Three accessions, one from Kenya and two from Malawi were evaluated. The seed quality and germination of the latter two were very low and only a few plants were obtained. Seeds of the Kenya accession were germinated in the greenhouse in October 1985, potted up, and transplanted into the field on March 5, 18, and April 1, 1986. Seeds were also planted in adjacent field plots on the same three dates. Most of the transplanted plants in the 1st planting date flowered and produced some seed. Only a few of the transplanted plants in the second planting date flowered due to increasing daylength. Essentially no flowering was observed on the transplanted plants of the third planting date, and none of the direct seeded plants produced flowers at any planting date. All plants proved to be very susceptible to soil borne fungi identified as *Fusarium* or *Rhizoctonia*. Another group of seedlings was started in the greenhouse in May and transplanted into the field in September. All plants died from the wilt disease before reaching maturity or flowering.

SUMMARY, CONCLUSIONS, AND FUTURE PLANS

The rationale for utilizing interspecific hybridization of cuphea as a means of recombining and releasing genetic variability for economically important characters, appears to be valid. The fertile hybrids between the herbaceous annual species *C. procumbens* x the perennial species *C. llavea* are producing a new array of genetic variability. The hybrids and backcross progenies are vigorous and flower profusely. Some would also appear to have horticultural potential as flowering plants. The single plant selections and bulk half-sib family populations made last summer in Iowa and Georgia will be further evaluated to determine if useful genetic variability can be identified and utilized.

A new series of cuphea interspecific hybrids made in Tucson and Phoenix will be grown out and evaluated. Desirable material will be shared with cooperating programs in Iowa, Georgia, and Oregon. Progenies of single plant selections and F_2 bulk populations of the procumbens x llavea hybrids will be evaluated in Iowa and Georgia. Oil and fatty acid analyses will be made on various parents, F_1's and progenies. Additional attempts will be made to restore fertility to several sterile hybrid combinations. More research will be conducted on developing methods for using colchicine to double the chromosome number and restore fertility through amphidiploidy. Additional attempts will be made to effect backcrosses of sterile F_1's to the various parental species as a means of releasing new sources of genetic variability.

The analytical results comparing oil percentage and fatty acid distribution among immature and mature seed lots of eight cuphea species have important economic implications. Cuphea has an indeterminate flowering and plant growth habit, and seeds shatter easily from the seed pods even before they reach full maturity. A real problem in obtaining economic yields from cuphea is being able to harvest or salvage a reasonable percentage of the seeds produced. Seed harvested at any one time or over a period of time exhibits a wide array of maturity. Since seed maturity does not significantly alter oil percentage or relative contents of the predominate fatty acids, we have the latitude to utilize various cultural and harvesting practices to maximize seed yields. This does not solve all our problems, but it is a very positive factor in our attempt to domesticate these species.

A series of single plant progeny of various accessions of _C. wrightii_, _C. lutea_, and _C. tolucana_ will be sent to the NRRC for analysis of oil and fatty acid distribution. This should give good information on the amount of plant-to-plant variability one might expect within these species. Analysis of these seed lots had been delayed since the quantity of seeds was relatively small in most instances. Seed maturity also ranged from green to fully mature. We had been concerned that variation in seed maturity would make valid comparisons between small seed lots difficult or impossible. Since seed maturity appears to exert only a minor effect on oil content and fatty acid distribution, we should be able to determine if plant-to-plant variation exists within these breeding populations.

Reduction in funding level for cuphea research is hampering progress. Support of cooperative research on interspecific hybridization and cytogenetics at the University of Arizona was terminated since funding levels were decreased by the transfer of funds to Ames, IA. In addition, when funds for the specific cooperative agreement at Oregon State were tranferred to Ames, IA, an amount of funds sufficient to restore the Gramm-Rudman reductions were taken from the project's base funding, and also transferred to Iowa. This reduced funding is severely limiting the cytogenetic aspects of the project, which are vitally essential to the interspecific hybridization effort. Steps must be taken to replace the anticipated loss of the biological technician on the project in June 1987. Additional technical help is needed for the whole new crops effort in the area of cytology and cytogenetics to replace the loss of cooperative support in this area from the University of Arizona.

The replicated yield trial utilizing an essentially unselected bulk population of _Lesquerella fendleri_ provides strong support for continued research on its development as a new crop for arid lands. The performance of progeny of single plant selections showed increases of about 30% in seed yield after only one cycle of selection. The yield of the highest selection (around 1740 kg/ha of cleaned seed) is approaching an economically viable seed yield. It is concluded that selection can significantly improve the plant type and yielding capacity of lesquerella. Additional increases are foreseen with increased breeding effort and the development of optimal cultural and water management practices. Additional selections will be made within a border planted

to various germplasm lines of _L. fendleri_ to start a new breeding cycle. Special emphasis will be placed on increased plant height in addition to seed yield.

Obtaining some flowering on the apparently photosensitive plants of _Vernonia galamensis_ is encouraging. However, since all plants tested were extremely susceptible to soil borne fungi, it is apparent that new sources of resistant germplasm are needed if any significant progress is to be made in the development of this plant as a new crop for this area. No additional research on vernonia is planned until new germplasm accessions are received.

PERSONNEL

A. E. Thompson and W. J. Allen

Table 1. Quality constituents of Cuphea species seed separated into two maturity groups.

Species & Location	Maturity Score		1000 Seed Weight (g)		Oil %		C10:0 %		C12:0 %	
	Green	Mature	Green	Mature	Green	Mature	Green	Mature	Green	Mature
C. wrightii:										
Davis, CA - 1982	5	8	1.595	1.728	34	34	35	33	56	58
Davis, CA - 1983	5	8	1.536	1.726	34	33	33	33	54	56
Corvallis, OR - 1983	4	7	1.484	1.692	36	35	38	37	51	52
Corvallis, OR - 1983	3	6	1.570	1.838	33	34	34	34	55	56
Phoenix, AZ - 1984	2	6	1.403	1.656	28	29	35	34	54	54
Phoenix, AZ - 1984 GH	4.5	5.5	1.795	1.992	35	33	36	33	51	54
Medford, OR - 1985	2	5	1.523	1.694	35	35	35	35	55	54
Medford, OR - 1985 RT	4	7	1.584	1.761	35	34	39	38	49	50
Ontario, OR - 1985 RT	1	4	1.570	1.656	36	36	38	37	50	53
Jacksonville, IL - 1985 RT	2	5	1.354	1.629	34	34	34	33	55	56
Isabela, PR - 1985 RT	6	8	1.514	1.576	34	34	35	33	57	56
Mean ($\bar{x}$)	3.5	6.3	1.539	1.723	34.0	33.7	35.6	34.5	53.4	54.5
C. tolucana:										
Corvallis, OR - 1983	6	9	1.120	1.309	36	37	24	23	65	66
Phoenix, AZ - 1984 GH	5	9	1.188	1.173	35	38	22	22	67	67
C. wrightii x C. tolucana:										
Corvallis, OR - 1984	5	7	1.938	2.190	33	34	31	31	58	57
Phoenix, AZ - 1984	5	8	1.650	1.770	34	33	21	20	66	66
C. laminuligera:										
Corvallis, OR - 1984	5	8	2.182	2.209	34	35	30	29	59	59
Corvallis, OR - 1985	4	8	2.094	2.092	30	29	30	31	57	57
C. lutea:										
Corvallis, OR - 1985	2	8	2.262	2.580	29	30	29	28	38	37
Phoenix, AZ - 1985 GH	3	8	1.845	2.110	29	28	27	27	41	39
C. paucipetala:										
Corvallis, OR - 1983	4	9	1.593	1.821	36	34	89	89	2.3	2.0
C. leptopoda:										
Corvallis, OR - 1984	7	9	3.856	4.133	36	37	88	91	3.4	2.1
C. procumbens:										
Phoenix, AZ - 1984 GH	3	7	4.537	4.680	32	32	87	85	2.4	2.0

Table 2. Correlations among Cuphea wrightii seed characteristics (n - 2 = 20)

	Maturity Score	1000 Seed Weight	Oil %	C10:0 %	C12:0 %
Maturity Score	--	+.5404**	-.0390	-.3248	+.3320
1000 Seed Weight		--	+.1025	-.1312	-.0307
Oil %			--	+.4137	-.2779
C10:0 %				--	-.8479**

** Significantly different from zero at the 0.01 probability level.

Table 3. Effect of plant population on yield of Lesquerella and performance of 10 best half-sib families—1985-86.

	Plant Population (Plants/ha)	Seed Parameters: Seed Yield (kg/ha)	Seed Weight/ Plant (g)	1000 Seed Weight (g)	Harvest Index	Plant Parameters: Biomass Dry Weight (kg/ha)	Plant Dry Weight (g)	Plant Height (cm)	Plant Width (cm)
	97,500	1008	10.4	.604	.175	5737	59.1	25.7	42.6
	131,250	1091	8.4	.600	.178	6096	46.9	26.8	43.7
	197,000	1240	6.3	.595	.180	6910	35.3	28.4	45.0
	222,250	1168	5.5	.601	.175	6645	31.1	28.9	45.8
	344,500	1256	3.7	.586	.174	7226	21.2	28.8	45.2
	1,103,250	1364	1.3	.574	.155	8761	8.3	34.5	49.8
Mean ($\bar{x}$)	349,292	1188	5.9	.593	.173	6896	33.6	28.8	45.3
1986 Selected Bulk - 10 Best Half-Sib Families									
Range: LO	170,000	1391	1.7	.542	.139	7233	9.6	31.3	53.5
HI	903,333	1740	10.0	.726	.234	16,798	55.6	39.2	63.6
Mean ($\bar{x}$)	481,000	1573	3.3	.621	.150	10,453	21.7	35.6	57.3

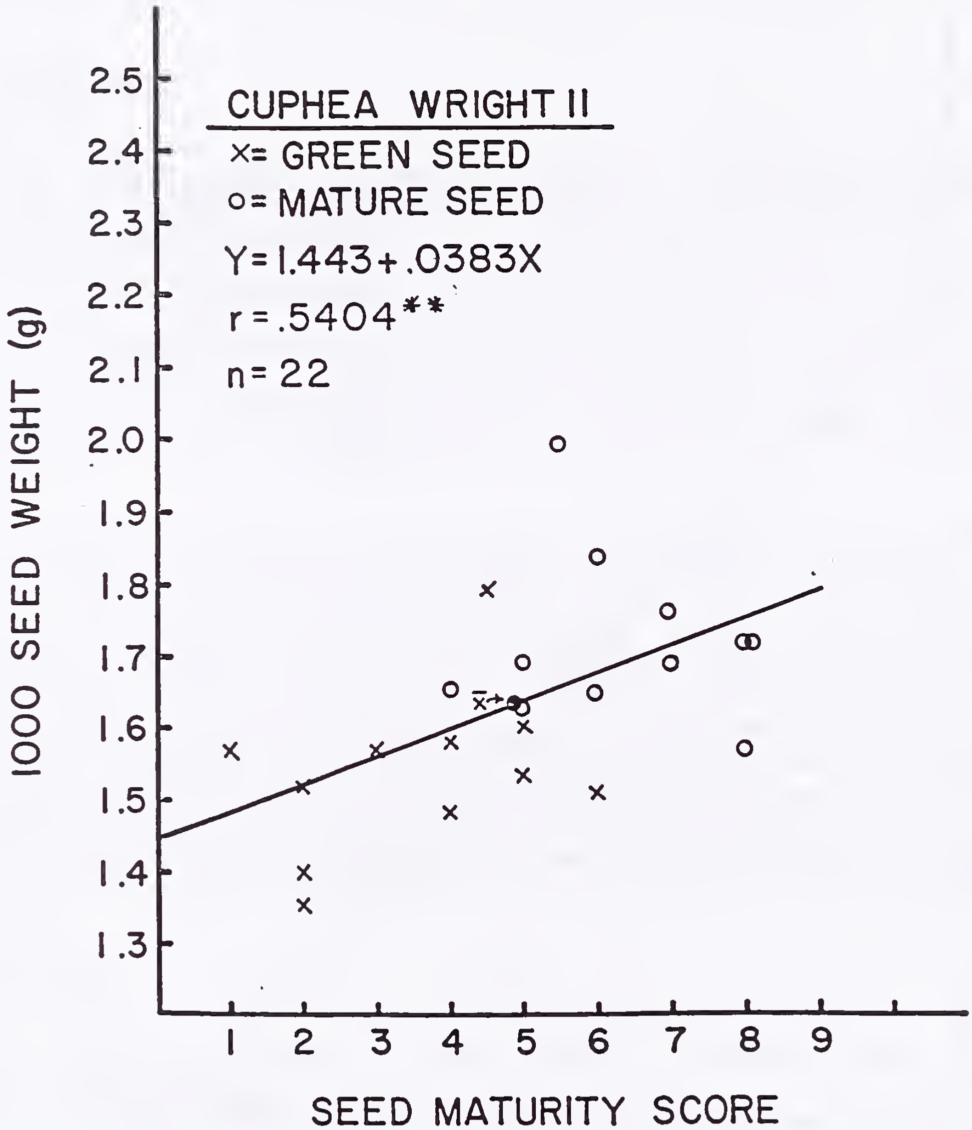


Fig. 1. Regression seed maturity score on 1000 seed weight of <u>Cuphea wrightii</u> seed samples separated on the basis of seed maturity.

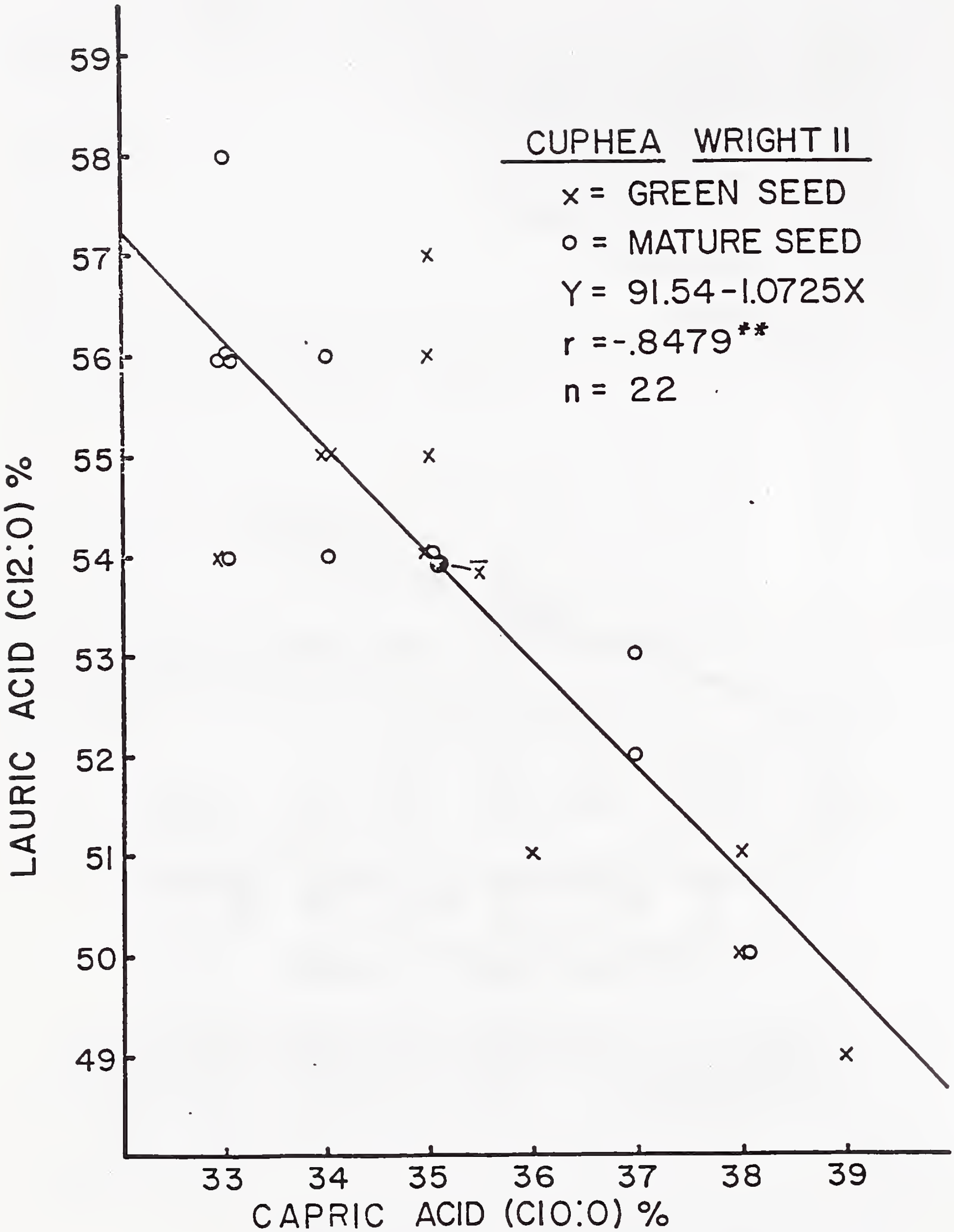


Fig. 2. Regression of capric acid content on content of lauric acid in Cuphea wrightii seed samples separated on the basis of seed maturity.

TITLE: GUAYULE GERMPLASM ENHANCEMENT FOR INCREASING NATURAL RUBBER AND RESIN PRODUCTION

STRATEGIC PLAN: 2.1.03.1.b CRIS WORK UNIT: 5422-20160-005

INTRODUCTION

The United States is totally dependent upon imports of natural rubber used for industrial and defense purposes. The annual cost of the import amounts to nearly $1 billion. In addition to the unfavorable effect on this country's balance of payment, the supply of natural rubber in Southeast Asia is frequently subjected to volatile economic as well as political conditions. Successful development of guayule as a new domestic crop could aid the overall agricultural economy of the U.S. by diverting acreage of surplus crops into production of noncompetitive alternative crops. Production of a new crop that may be better adapted than conventional crops to arid conditions would provide additional benefits to the Southwest.

Congress, in order to prevent future vulnerability, passed the Native Latex Commercialization and Economic Act in 1978, and replace it with the Critical Agricultural Materials Act in 1984. The Act provides for the development of an economically feasible system for the culture and commercialization of guayule and other new crops to benefit the nation and promote economic development. Various research components on the cultivation and processing of guayule rubber have been in force since 1978. The Guayule Researcher's Planning Meeting held October 4-5, 1983, at Mesa, AZ, clearly identified breeding, germplasm and genetics as the highest priority research need. The conferees expressed strong support for USDA-ARS to initiate research and provide leadership in this area. This new project was formally initiated in July, 1986 to address this need.

PROCEDURE

The research activities on the project are organized under the following four objectives:

(1) Improve rubber yield of guayule and concomitant traits such as quality, seedling and mature plant vigor, plant architecture, capability for regeneration following clipping harvest, and tolerance to salinity, drought, diseases, and pests through the development of genetically enhanced germplasm and cultivars.

(2) Develop sampling methods and evaluate rapid chemical and physiological methods to increase efficiency of breeding and selection, and genetic analysis of rubber and resin yield and quality.

(3) Conduct basic genetic research on components of yield and quality, and the heritability of the asexual, apomictic reproductive mechanism of guayule, and to utilize this information in the development of more efficient hybridization and breeding methods.

(4) Participate in the Guayule Uniform Regional Variety Trial.

The new USDA/ARS guayule germplasm enhancement/genetics project is designed to closely interact with, supplement, support, and provide coordination to the existing breeding and genetic projects at the University of Arizona and University of California-Riverside. There is sharing and utilization of jointly planned and managed research plantings of guayule on the Maricopa Agricultural Center and other field facilities of the University of Arizona.

RESULTS AND DISCUSSION

A 3-acre plot of diverse guayule breeding material was established in 1982 on the Wong Farm near Marana, AZ. The planting was examined for genetic variability and selection potential in cooperation with Dr. D. T. Ray of the University of Arizona. Considerable variability was observed both within and between plots for plant vigor and growth habit, plant height and spread, number of branches, biomass production, flowering, foliage color, leaf size and shape, and disease reaction. Plants within 234 plots were judged to be uniform and most likely the progeny of apomictic selections. A total of 423 single plant selections were made within 132 plots that exhibited significant plant to plant variability. Each single plant selection was harvested in February, 1986 by clipping the tops at a uniform height of 10 cm. Five plants from each uniform plot were likewise harvested and bulked. After analysis of rubber and resin, 180 of the 423 selections had an acceptable or "good" rubber percentage. Regeneration of vegetative growth was scored in May, and plant vigor and survival further evaluated in August, 1986. Of the 180 "good" selections, only 80 survived (Table 1). Of this total 64 had good biomass and consequently good rubber yield (grams/plant), but only 37 had strong regeneration and survival after clipping. The distribution of vigor/regeneration scores for the total population and the 37 "superior" selections are summarized in Table 2.

Data from selected single plants (Table 3) were taken for fresh weight (0.05-7.22 kg), dry weight (0.03-4.79 kg), plant height (23-126 cm), plant width (18-141 cm), stem number 4-44), and mean stem diameter (0.50-2.38 cm). Total and mean stem cross sectional area and circumference, and the ratio of total circumference to total area were calculated. Rubber (2.16-9.54%; 1.2-238.0 g/plant) and resin (3.36-10.64%; 2.0-299.7 g/plant) were analyzed by NIR. Statistical relationships among various yield and plant growth parameters were calculated (Table 4). The highest correlations of rubber yield (g/plant) were with dry and fresh weight of plant, plant height and width, and total cross sectional area of the stems. Regressions of rubber yield on dry weight of plants, plant height, and total cross sectional area of stems were calculated within the population of 37 superior single plant selections and plotted in Figs. 1-3. Twelve of the 37 selections had rubber yields in excess of 120 g/plant, which equates to an annual rubber yield of over 1150 kg/ha. Of the 234 selected uniform plots, a total of 42 were identified as being superior.

The 26 original USDA lines that originated from the Emergency Rubber Project in the 1940's were transplanted at the University of Arizona,

Casa Grande Highway Farm in Tucson in October and November 1981, and grown for 4.33 years for seed increase. On March 19, 1986, four 2-plant repetitions of whole plants were dug from each line. At the same time, four 2-plant repetitions were cut 10 cm above the soil line simulating harvest by clipping. Lines were characterized for ploidy level, height, width, dry weight, percent rubber, percent resin, rubber yield, and resin yield (Table 5). Rubber quality is currently being evaluated, but this work is not yet completed.

Mean rubber percent and annual rubber yields for clipped and whole plant samples ranged from 3.70-6.14% and 171-558 kg/ha/yr. Resin production ranged from 4.72%-7.86% and 230-737 kg/ha/yr, and biomass (plant dry weight) ranged from 4,147-10,502 kg/ha/yr. Whole plants yielded on average 27% more dry weight than the clipped branches alone. However, the mean rubber percent was lower in whole plants (4.5%) than in the clipped branches (5.2%). The same was observed for mean percent resin, with whole plants averaging 6.5% and the clipped branches 6.9%. Whole plants averaged 15% greater rubber yields and a 22% increase in resin yields per hectare over the clipped branches. The high rubber lines, when whole plants were harvested, were 11604 and 11693. Lines 11693, N565, and 11604 were the highest resin yielders when whole plants were harvested. The highest yielding lines when branches were clipped were 36-Chromosome and 11693 for both rubber and resin.

Ploidy level was determined by Dr. Ray by meiotic analysis of pollen mother cells. Chromosome counts for 17 of the 26 lines have identified plants with ploidy levels from 2n (36) to 8n (144). Twelve of the 17 lines are predominantly 3n (54). Thirty-nine 36-chromosome plants were analyzed: 19 were found to be 2n; 17 3n; 1 4n; and 2 aneuploid between 2n and 3n. B-chromosomes were found in 109 of 173 plants analyzed. Cytological examination will continue toward evaluation of all 26 lines.

An experiment was conducted to determine the effects of postharvest storage on rubber and resin quantity and quality. Six whole plants of each of the 26 USDA lines were harvested on March 19, 1986, and stored out of doors. One plant of each line was sampled at 2, 4, 8, 12, 16, and 24 weeks after harvests and analyzed for rubber and resin content. At the time of harvest, chipped samples from the four-2-plant replicates for the clipped branch and for the whole plant samples for each of the 26 lines were separately bulked. These 52 bulked, chipped samples were held in paper bags under ambient temperature conditions in an air conditioned room at ± 20°C. Samples from each were taken and analyzed for rubber and resin content on the same time schedule as the 26 whole plant samples. Statistical analysis of this experiment is still in progress.

The Second Guayule Uniform Regional Variety Trial was established on October 8, 1985. The first harvest of seedling plants was made on March 3, 1986, and samples were sent to Dr. G. Earle Hamerstrand, NRRC, Peoria, IL, for analysis. A cooperative replicated experiment to evaluate 29 new guayule selections from the University of California-Riverside program was established on October 14-15, 1986, at the Maricopa Agricultural Center. This planting duplicates two plantings

established in Riverside and Palmdale, CA. This experiment should provide needed information for estimating genotype-environment interactions.

SUMMARY AND CONCLUSIONS

The breeding and selection phase of the project has only just started, but promising results are being obtained. Of the 423 single plant selections and 234 uniform, apomicitic lines selected, 37 superior single plant and 42 superior uniform lines were identified. These lines have a combination of high rubber yield and capacity for vigorous regrowth following harvest by clipping. The ability to regrow after clipping is a very important factor since it will allow reharvesting after 1 to 2 years without replanting. This should significantly decrease the cost of production, and increase the amount of rubber and resin that can be harvested on an annual basis from a given land area.

Approximately one-third of the 37 superior single plant selections had rubber yields over 120 g/plant, which equates to yields of over 1150 kg/ha/year at the standard plant population of 27,500 plants/ha. These as well as the other selections and lines will be retested in 1987 to verify the 1986 results. It seems reasonable to expect that some of these lines will continue to produce at this high level. If so, cultivars should result that will produce economically viable yields. The selected material should also be of value as parents of crosses designed to recombine desirable features from other breeding programs. However, it must be recognized that germplasm development and breeding and evaluating new, high yielding cultivars takes time and the research effort must be financially supported and sustained over a sufficiently long period of time.

The superior single plant selections and superior uniform lines will be resampled in February-March, 1987 to verify the original performance data on yield and other plant characteristics. An experiment is being designed to sample additional plants on a single plant basis within the same field plots that contain the superior uniform lines. Approximately 20 to 25 plants are available in each plot in addition to the original 5 plants sampled. This will give us a good reevaluation of our past year's data and a measure of plant-to-plant variability within the putative apomictic lines. Both seeds and cuttings will be harvested from each plot to provide planting material for reestablishment of superior selections and lines at the Maricopa Agricultural Center.

The planting of the original 26 USDA lines at the University of Arizona experimental farm in Tucson offered an opportunity to evaluate all of the lines for the first time under a uniform environment and location. The lines exhibited highly significant differences for rubber and resin percentage and yield as well as for biomass production, plant height, and width. We were also able to assess the relative differences among lines under two harvesting methods -- clipped branches and whole plants

including the roots. These data will serve as a needed base line with which future production data can be compared. The data on postharvest storage performance of the various lines will also be useful for devising recommendations for handling harvested plant material before processing. We may also be able to identify additional genetic variability among the lines, which will be useful in our breeding and selection program.

Our interest in the 26 USDA lines led to an examination of the source of the original germplasm and possible relationships among the lines. We determined that 21 of the lines came from the state of Durango, Mexico. The apparent narrowness of the germplasm base is accentuated by the fact that 15 of the lines descended from the Powers et al. collection #4265, which was a bulk of only 5 selected plants at one location. In addition, 5 of the Hammond and Hinton collections came from one general location on a single hacienda. The diploid 36-Chromosome material also came from a nearby location. It would appear that a broader germplasm base is needed to accelerate the development of germplasm and cultivars. However, a rather surprising amount of variability exists within the germplasm population represented by the 26 USDA lines. Since much of the guayule still existing in native stands is introgressed to a varying degree with mariola (Parthenium incanum), the rubber content of accessions most probably would be lower than that found in existing, selected germplasm. We conclude that the best current strategy is to work with existing material rather than mounting additional collections from the native stands.

The postharvest storage study will be expanded by resampling the population of 26 lines and will be completed with the analysis of rubber molecular weight. Molecular weight will also be run on the various selected plants and uniform plots.

Data collected on the various components of yield and plant growth will be subjected to statistical analysis to develop selection indices by path coefficient and factor analyses. These data should prove very useful in our breeding and selection program to maximize genetic gain. Appropriate crosses will be made among selected guayule plants and lines to recombine genetic variability, and allow for selection of genetic combinations giving rise to enhanced germplasm and cultivars. These crosses will be based on information gained from screening, evaluation, and characterization of useful genetic variability, and from basic genetic studies on the nature of and ways to manipulate apomixis and other reproductive mechanisms such as self-incompatibility. Appropriate breeding and genetic populations will be established to facilitate selection and aggregation of desirable genetic traits into useful, improved lines. Enhanced germplasm will be made available to cooperative breeding programs for evaluation and utilization in the development of improved high-yielding breeding lines and cultivars.

PERSONNEL

A. E. Thompson, D. A. Dierig, F. S. Nakayama, and S. G. Allen.
D. T. Ray, Plant Science Department, University of Arizona, Tucson, AZ, cooperating.

Table 1. Disposition of 423 guayule single plant selections -- Wong Farm, Marana, AZ -- 1986.

	"Good" Selections			"Superior" Selections		
	No.	Survived 8/5/86	Seed Harvested	No.	Survived 8/5/86	Seed Harvested
Number of Selections	180	80	48	64	37	25
% Total Selections	42.5	18.9	11.3	15.1	8.7	5.9
% of "Good" Sels.		44.4	26.7	35.6	20.6	13.9
% of "Superior" Sels.					57.8	39.1

Table 2. Distribution of vigor/regeneration scores among 423 guayule single plant selections -- Wong Farm, Marana, AZ -- 1986.

	Vigor/Regeneration Score							
	0	1	2	3	4	5	Total	Mean ($\overline{x}$)
Total Population:								
Number - 5/8/86	54	229	50	38	29	23	423	1.59
Number - 8/5/86	244	17	48	57	30	27	423	1.27
% - 5/8/86	12.8	54.1	11.8	9.0	6.9	5.4		
% - 8/5/86	57.7	4.0	11.4	13.5	7.1	6.4		
"Superior" Selections:								
Number - 5/8/86	0	10	9	9	5	4	37	2.57
Number - 8/5/86	1	2	11	8	9	6	37	3.08
% - 5/8/86	0	27.0	24.3	24.3	13.5	10.8		
% - 8/5/86	2.7	5.4	29.7	21.6	24.3	16.2		

Table 3. Range of variability of yield and plant characteristics among guayule single plant selections.

Yield and Plant Characters	Superior Selections			Total Population		
	Range		Mean	Range		Mean
	Lo	Hi	(n=37)	Lo	Hi	(n=423)
Rubber yield-g/plant	60.3	222.5	106.6	1.2	238.0	60.5
Rubber %	4.65	9.34	7.08	2.16	9.54	6.08
Resin yield-g/plant	54.4	288.3	122.5	2.0	299.7	70.8
Resin %	4.22	9.83	8.02	3.36	10.64	7.01
Fresh weight-kg	1.21	4.92	2.33	.05	7.22	1.54
Dry weight-kg	.78	3.22	1.54	.03	4.79	1.00
Dry weight %	55.1	72.4	66.1	48.7	79.9	64.9
Plant height-cm	56	126	83.8	23	126	71.3
Plant width-cm	69	132	92.3	18	141	79.1
Stem number	7	32	15.5	4	44	16.5
Mean stem diameter-cm	.78	2.08	1.27	.50	2.38	1.02
Total stem circumference-cm	31.4	94.2	60.2	9.4	110.0	50.2
Mean stem circumference-cm	2.45	6.54	4.00	1.57	7.46	3.19
Total x-sectional area-cm^2	9.8	47.1	25.5	1.96	54.4	17.9
Mean x-sectional area-cm^2	.70	3.53	1.76	.20	4.91	1.18
Regeneration/vigor score:						
5/8/86	1	5	2.57	0	5	1.59
8/5/86	0	5	3.08	0	5	1.27

Table 4. Correlation coefficients (r) of rubber yield (g/plant) with various yield and plant characters in guayule single plant selections.

Yield and Plant Characters	Superior Selections (n = 37)	Total Population (n = 423)
Rubber %	-.06	.27**
Resin %	.10	.26**
Resin yield-g/plant	.93**	.95**
Fresh weight-kg	.63**	.92**
Dry weight-kg	.92**	.93**
Dry weight %	.14	.16*
Plant height-cm	.56**	.70**
Plant width-cm	.53**	.72**
Stem number	.14	-.02
Mean stem diameter-cm	.43**	.57**
Total stem circumference-cm	.38**	.54**
Mean stem circumference-cm	.43**	.57**
Total x-sectional area-cm^2	.65**	.69**
Mean x-sectional area-cm^2	.52**	.56**

* Significantly different from zero at the 0.05 probability level.
** Significantly different from zero at the 0.01 probability level.

Table 5. Comparison of yield and plant characteristics of 26 USDA guayule lines harvested by whole plant and clipping (cut at 10 cm height) methods.

Yield and Plant Characters	Clipped Branches	Whole Plants	Range for 26 Lines[1]
Rubber %	5.19[b2]	4.48[a2]	3.70-6.14
Rubber yield-kg/ha[3]	1339[a]	1598[b]	742-2418
Rubber yield-kg/ha/yr[4]	309[a]	369[b]	171-558
Resin %	6.91[b]	6.46[a]	4.72-7.86
Resin yield-kg/ha[3]	1797[a]	2295[b]	998-3192
Resin yield-kg/ha/yr[4]	415[a]	530[b]	230-737
Fresh weight-kg/plant	1.40[a]	1.96[b]	0.99-2.50
Fresh weight-kg/ha[3]	38,500[a]	53,900[b]	27,225-68,750
Fresh weight-kg/ha/yr[4]	8,885[a]	12,438[b]	6,283-15,865
Dry weight-kg/plant	0.94[a]	1.29[b]	0.65-1.66
Dry weight-kg/ha[3]	25,830[a]	35,700[b]	17,970-45,510
Dry weight-kg/ha/yr[4]	5,961[a]	8,238[b]	4,147-10,502
Moisture %	32.67[a]	33.67[b]	28.94-37.26
Plant height-cm	84[a]	85[a]	71-96
Plant width-cm	70[a]	70[a]	60-80

1 Means for both clipped branches and whole plants.

2 Mean separation between 2 columns (clipped branches vs. whole plants) by Student-Neumann-Keuls' test at .05 probability level.

3 Assumed plant population = 27,500 plants/hectare.

4 Planted November 1981 -- harvested March 1986 = 52 months of growth.

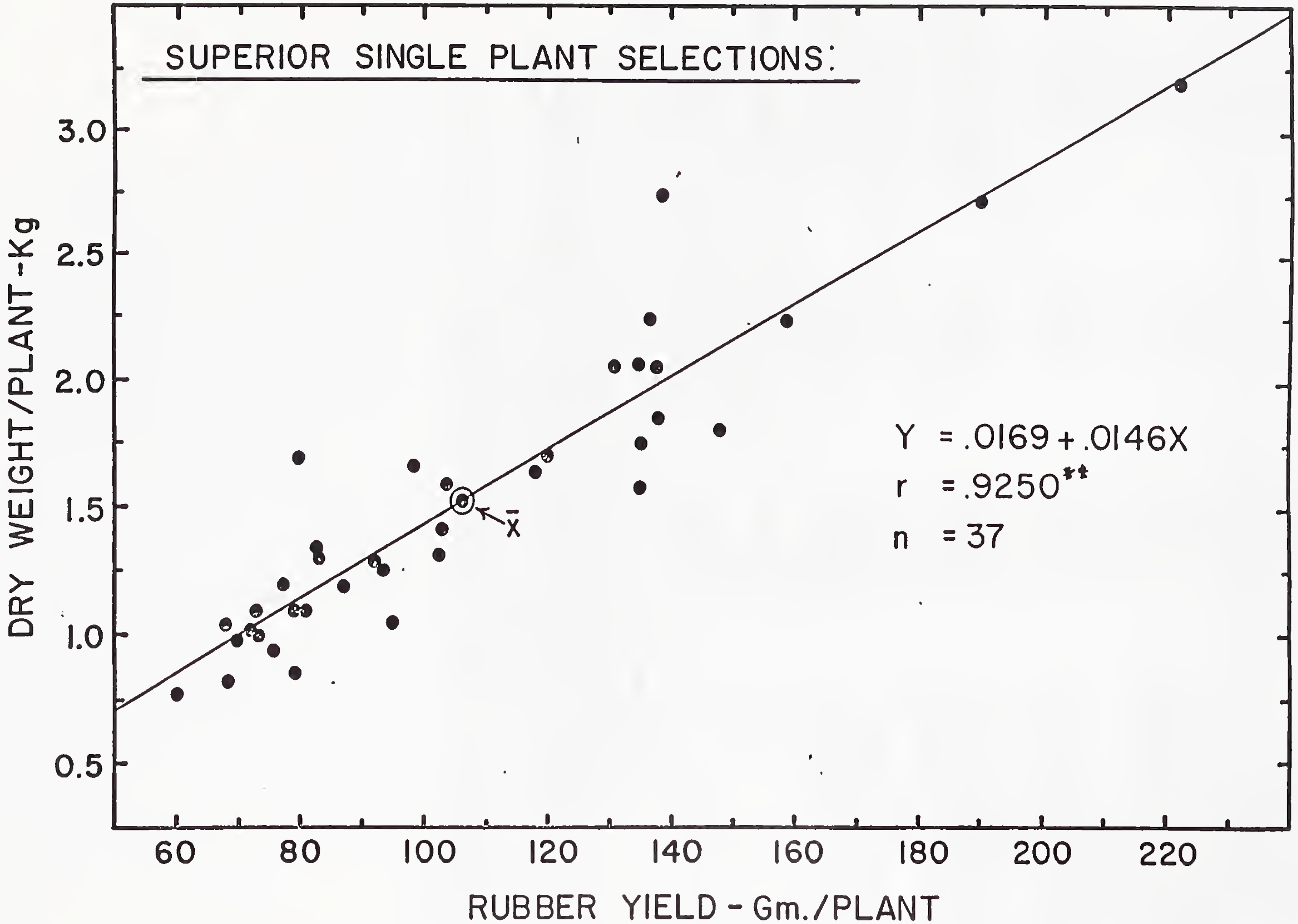


Fig. 1. Regression of guayule rubber yield on dry weight/plant.

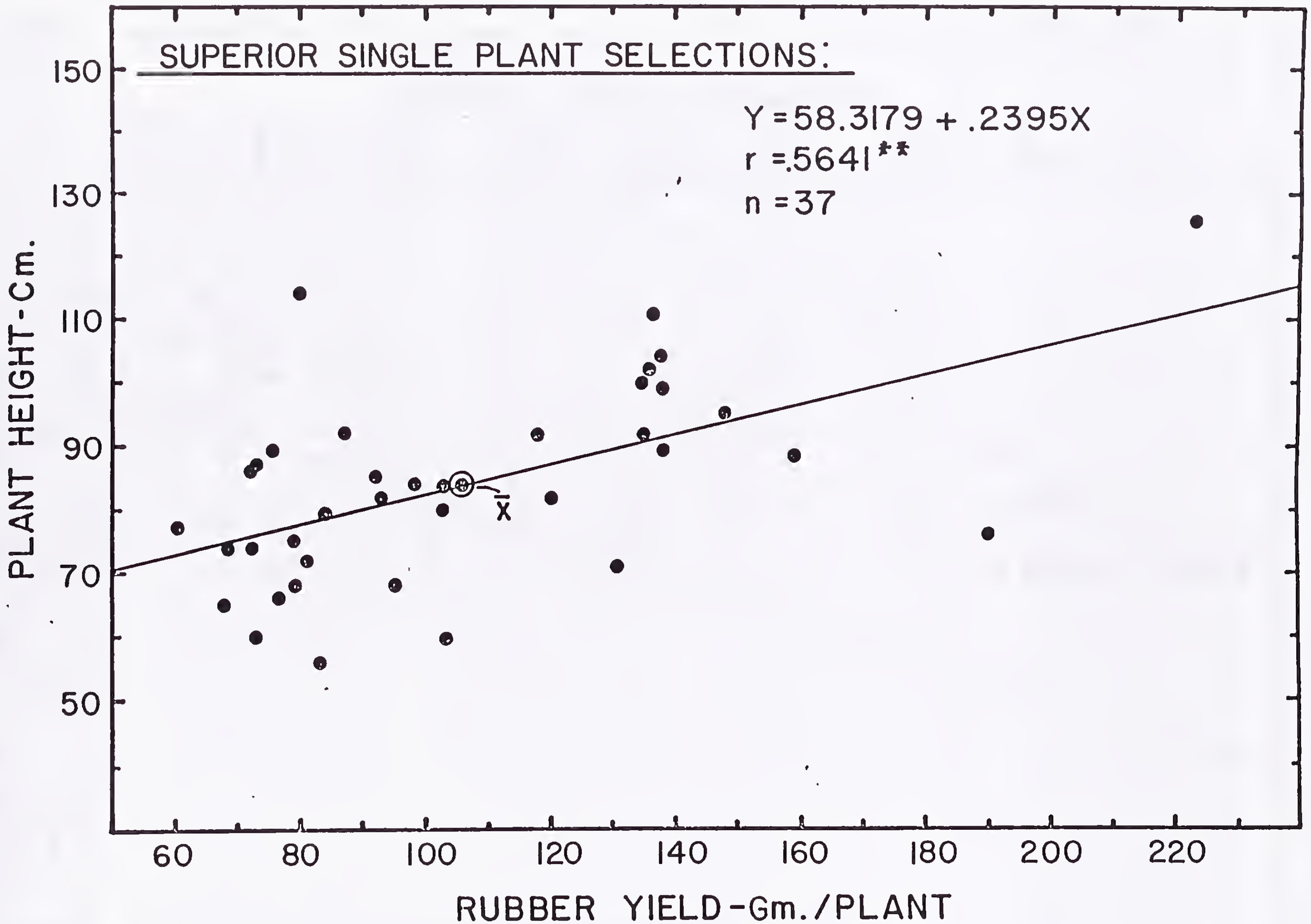


Fig. 2. Regression of guayule rubber yield on plant height.

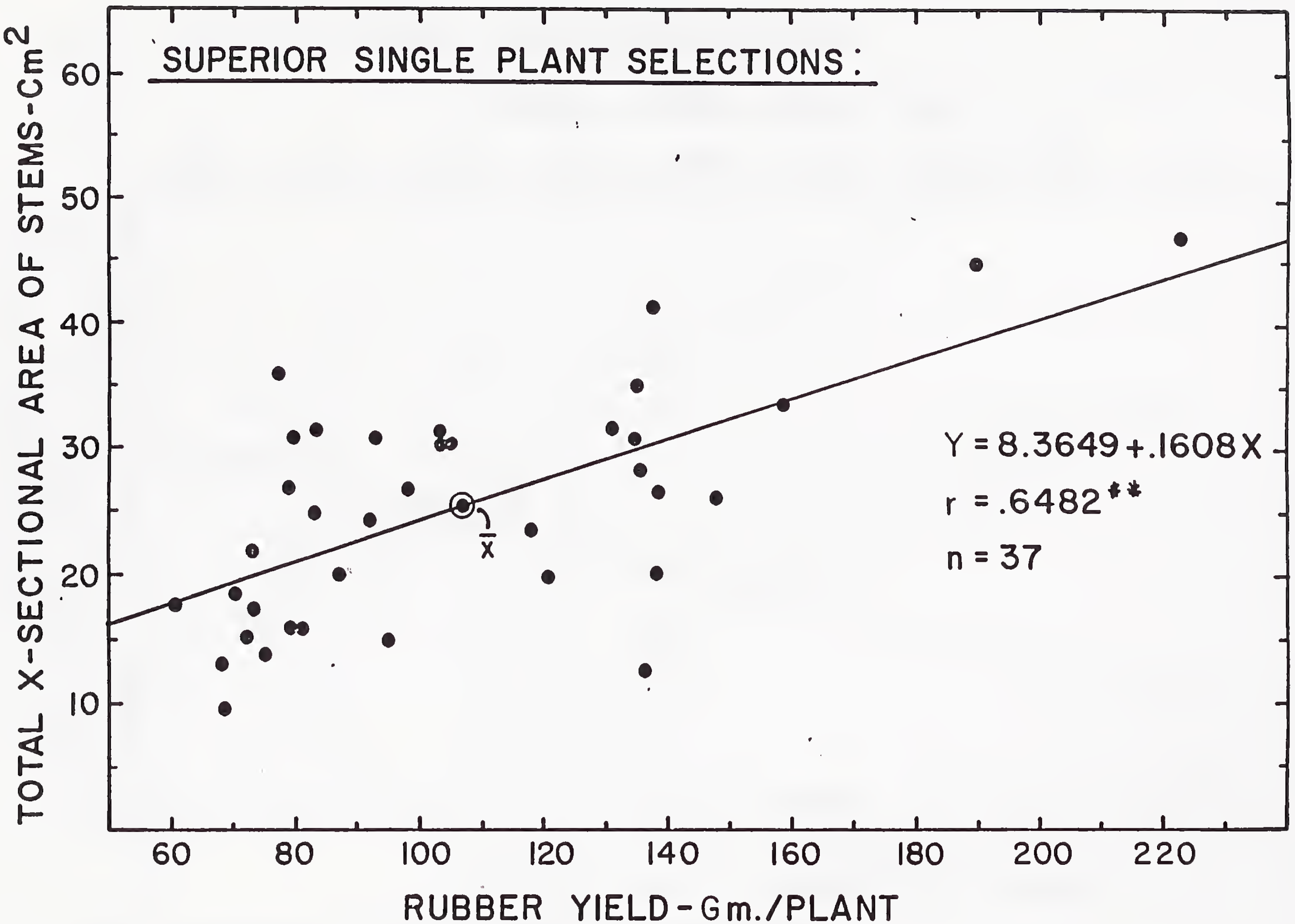


Fig. 3. Regression of guayule rubber yield on total cross sectional area of stems.

TITLE: SURFACE IRRIGATION MODELING

SPC: 1.3.03.1.d CRIS WORK UNIT: 5422-20740-003

STATUS OF MODELS

The border irrigation model developed by Strelkoff under contract to ARS has been made available for personal computers, such as the ARS Telex PC. A number of requests have been made for the program, which replaces the original zero-inertia model published by Strelkoff and Katopodes in 1977 and a modified version distributed by Clemmens in about 1980. A number of versions have been made available, with Version 7 being the most recent. A list of persons who have requested the computer programs is given below.

Version 7
- Jim Ayars, ARS Fresno
- Jorge L. Chambouleyron, Argentina
- B. L. Maheshwari, Australia
- M. Schiara, Italy
- Tom Ley, WSU
- Tom Spofford, SCS Washington
- John Dalton, SCS Montana
- Paul Williams, ARS Fort Collins
- Graham J. Weir, New Zealand
- Leland Hardy, SCS Arizona
- Marinus G. Bos, The Netherlands
- Allie Blair, NMSU
- Jim Bondurant, ARS Kimberly
- Wynn Walker, USU
- Brad King, ISU
- Vergil Backlund, SCS California
- Jan Feyen, Belgium

Prior Versions
- Ernie Gonzales, SCS New Mexico
- Paul Koluvek, SCS Portland
- Jim Garton, Joe Lord Inc., California
- Natalie Carrol, MSU
- Aws Aloui, CSU
- Pedro Souza, Portugal
- Nikolas Katopodes, U of Michigan
- Day Bassett, WSU
- Rien Jurriens, The Netherlands
- Eduardo Holzapfel, UC Davis
- E. Gorden Kruse, ARS Fort Collins

In addition, numerous other individuals have received the model from these individuals. Most of the requests are from researches, although one consultant has used the program extensively, and many SCS engineers are beginning to use it. It clearly needs to be used by technical people and not by the farmers or end users.

The general purpose surface irrigation (border and furrow) program is still under development. The zero-inertia portion has been programed, but has not been run successfully on PC's. The Kinematic Wave routines are currently under development.

BORDER IRRIGATION DATA ANALYSIS

A field study was initiated in 1978 by Clemmens and Dedrick on the U. of Arizona Cotton Research Center farm. Three fields were laser leveled to three different slopes (0.000, 0.0005, 0.001) in order to test the zero-inertia model under different conditions. Original testing was done in the fall of 1978 and spring of 1979, where only advance and recession were observed. Some ring infiltration and water surface data were collected on two of the level borders. When Clemmens left ARS in 1979, the project was dropped except for one set of data collected by Dedrick and Fangmeier in the fall of 1979. For this data set, both ring infiltration and water surface data were collected on two borders for each slope.

When Clemmens returned to ARS in 1980, these data were analyzed and compared with Clemmens' version of the zero-inertia model. This version did not allow for undulating field slopes and only considered plane fields. A volume balance program (Clemmens, 1982) was used to develop infiltration equations from the water surface data. Once an infiltration equation was developed, flow velocities were determined from which roughness constants could be evaluated.

In general, the model fit the data reasonably well. Differences in model versus actual stream behavior could easily be attributed to differences between assumed and actual infiltration and to the undulating slopes. These results were not published since the usefulness and accuracy of the zero-inertia model had already been established in the research community. However, very little data demonstrating accurate estimates of water surface profiles has been reported in the literature. The comparisons quickly become too voluminous for most journal articles.

Table 1 presents the preliminary data for irrigations on two borders at different flow rates on each of three slopes. Application times were adjusted according to flow rate, border length and border slope. Table 2 shows the profile data collected for border #1. These data were interpolated from raw hydrograph data so that the times represent advance times to each station. Advance and recession times observed and computed from profile data for border #1 are show in Table 3. Tables 4 through 13 present profile and advance data for borders 3, 4, 6, 7, and 9, respectively.

Infiltration constants for the Kostiakov infiltration function were developed from the volume balance procedure developed by Clemmens (1982). A log-log plot of average infiltrated depth versus average opportunity time for each volume balance time period is shown for each border in Figures 1 through 6. These points were fit with a straight line (power function) to obtain the Kostiakov infiltration constants. These constants are given in Table 14. The equations are plotted in Figure 7.

It was noted in preliminary runs of the zero-inertia model, that errors in predicted advance times resulted when the volume balance cumulative infiltration depth at a given time differed from the best fit equation cumulative depth. Errors in recession times were noted when the best fit line did not pass through the last volume balance point. Some curvature in the depth versus time relation indicates that the Kostiakov equation is not entirely appropriate in all cases. Recession times seemed to be predictable when data points from the volume balance procedure were fit for times greater than one hour. (Opportunity times ranged from about 3 to 6 hours). These curves are plotted in Figure 8. Ring infiltration data were taken on borders 1, 4, and 7. Best fit Kostiakov infiltration functions and the range of ring data are shown in Figure 9 and the equation constants are given in Table 14.

Table 15 shows the results of the analysis for Manning roughness coefficients. The borders were planted to alfalfa, which is typically assigned a roughness value of 0.15. The method for estimating roughness are clearly not very exact, owing to errors in the volume balance procedure, spatial variations in infiltration and roughness, etc. Several observation were made from the raw data.

1. Manning roughness values decreased with increasing flow rate. This trend matches theoretical predictions.
2. Manning roughness values were not affected by field slope.
3. Roughness seems to decrease down the border. This in part contradicts 1. above.

Values chosen for roughness estimate were obtained by discarding clearly bad values (e.g., out of Reynolds number range), taking the median over time at each station, and then taking the average of these median values. The resulting values (Table 15) are all near the estimated 0.15. The values given in Table 15 were used without modification in the border irrigation model. It has been found that roughness values have a small effect on advance and recession predictions. However, the effect on water surface profiles may be more significant.

The advance and recession curves for border #1 are shown in Figure 10. As noted from Figure 1, the best fit curve matches the points both early and late in the irrigation. Thus, as expected, the advance and recession curves were well predicted. Figures 11 and 12 show the profiles and depth hydrographs, respectively, both predicted and observed. Some errors in predictions are noted, however many appear to be the result of either the rough bottom profile, or errors in roughness estimates. In general, the hydrograph peaks are under-predicted, while the falling legs are well predicted. The 1980 version of the zero-inertia model could not handle an undulating profile.

Figure 13 shows the advance and recession curves for border #3. Since the best fit volume balance curve of Figure 2 under predicts infiltration, one would expect predicted recession times to be delayed, as in Figure 13c, while predicted advance times are reasonable. However, when the best fit volume balance curve after 1 hour is chosen, as in Figure 14, recession is well predicted, while advance is not. A slight slope

was fit to field elevation data which improved recession prediction. Figures 15 and 16 give the profiles and depth hydrographs, respectively. It appears that upstream depths are under predicted and downstream depths are over predicted suggesting an under-prediction of roughness effects.

Figures 17, 18 and 19 show the advance and recession, profile and depth hydrograph curves for the steepest slope tested. Advance and recession are well predicted except for the recession lag time which is greatly under-predicted. Also of interest is the non-smooth nature of the depth hydrograph at station 450.

Some problems were noted in data analysis for border 6 (e.g., negative infiltrated depths at small times) owing to the poor assumptions for the tip cells of the volume balance model. This in part may have distorted the infiltration curve shown in Figure 4. Thus only infiltration after 1 hour was used to determine a Kostiakov infiltration function (a modified or branch Kostiakov would be better). Figure 20 shows that with this function, the model predicted advance and recession well, including recession lag time. The reason that the model predicted recession lag time for one of the steep border and not for the other is not clear. Figures 21 and 22 show profiles and depth hydrographs.

Volume balance infiltration for field #7 in Figure 5 showed a reverse curvature from the other borders. Errors in the volume balance procedure at short times was suspected, so only the infiltration after 1 hour was used to estimate k and a. Figure 23 shows good agreement between predicted and observed advance. Profiles and depth hydrographs (Figures 24 and 25) were also reasonably well predicted.

Figure 26 shows that the original volume balance data did a good job of predicting advance data for border 9, but not so good at predicting recession. Adjusted infiltration (Figure 27) improved recession prediction, but caused poorer advance predictions. In addition, recession lag time was not well predicted. Profiles and depth hydrographs are shown in Figures 28 and 29.

It is clear that more analysis should be done on determining the effects of different parameters on the predictions of advance, recession and water distribution. This data set may aid in that process.

PERSONNEL

A. J. Clemmens, A. R. Dedrick

Table 1. Physical characteristics of borders and irrigation tests on Cotton Research Center farm, 8/15/79.

Border	1	3	4	6	7	9
No. Sta.	8	8	8	8	8	8
Time periods	15	14	17	20	16	12
Unit flow rate cfs/ft	0.06745	0.10163	0.06775	0.1016	0.0677	0.1016
Applic. time min	53	33	37	25	43	26
Bottom slope	0.000	0.000	0.001	0.001	0.0005	0.0005

Table 2. Profile data for CRC border #1, 8/15/79.

Station distance (ft)	0	50	150	250	350	450	550	610
station elevation (ft)	.11	.08	.11	.09	.07	.13	.08	.09
Time (min)	**station depths (ft)**							
2	.200	.0						
12	.390	.350	.0					
24	.490	.464	.270	.0				
37	.560	.537	.377	.260	.0			
52	.610	.609	.465	.380	.268	.0		
70	.365	.390	.336	.331	.299	.179	.0	
90	.270	.297	.260	.262	.254	.161	.168	.0
120	.225	.251	.213	.222	.233	.149	.174	.150
180	.141	.171	.131	.153	.173	.123	.177	.167
240	.105	.135	.096	.118	.143	.086	.135	.125
300	.071	.101	.069	.084	.105	.053	.102	.092
360	.042	.072	.036	.051	.070	.015	.069	.059
470	.015	.045	.0	.025	.045	.0	.042	.032
480	.0	.021		.0	.020		.011	.0
540		.0		.0	.0		.0	

Table 3. Advance and recession data for CRC border #1, 8/15/79.

	observed			computed		
distance	advance	reces.	opport.	advance	reces.	opport.
(ft)		(min)				
0	0	450	450	0	453.3	453.3
50	2	519	517	2	532.5	530.5
150	12	402	390	12	425.5	413.5
250	24	462	438	24	477.7	453.7
350	37	510	473	37	528.0	491.0
450	52	414	362	52	383.7	331.7
550	70	518	448	70	501.3	431.3
610	90	480	390	90	491.1	401.1

Table 4. Profile data for CRC border #3, 8/15/79.

Station distance (ft)	0	50	150	250	350	450	550	610
station elevation (ft)	.15	.14	.09	.12	.08	.09	.06	.08
Time (min)	station depths (ft)							
2	.160	.0						
10	.440	.373	.0					
19	.510	.460	.351	.0				
30	.610	.576	.471	.283	.0			
43	.380	.390	.419	.328	.266	.0		
60	.249	.259	.301	.250	.250	.187	.0	
76	.192	.202	.239	.202	.197	.178	.147	.0
105	.143	.153	.191	.151	.175	.158	.172	.145
165	.086	.096	.132	.092	.129	.121	.151	.131
225	.050	.060	.086	.058	.093	.086	.119	.099
285	.020	.030	.059	.029	.056	.056	.085	.065
345	.0	.0	.021	.0	.020	.028	.045	.025
405			.0		.0	.0	.012	.0
465	.0						.0	

Table 5. Advance and recession data for CRC border #3, 8/15/79.

distance	observed			computed		
	advance	reces.	opport.	advance	reces.	opport.
(ft)		(min)				
0	0	300	300	0	325	325
50	2	311	309	2	345	343
150	10	377	367	10	378.2	368.2
250	19	354	335	19	345	326
350	30	372	342	30	378.3	348.3
450	43	426	383	43	405	362
550	60	420	360	60	426.8	366.8
610	76	360	284	76	382.5	306.5

Table 6. Profile data for CRC border #4, 8/15/79.

Station distance (ft)	0	50	150	250	350	450	550	620
Station elevation (ft)	.83	.78	.69	.60	.48	.40	.35	.31
Time (min)	**station depths (ft)**							
1	.120	.0						
8	.360	.324	.0					
19	.410	.387	.292	.0				
35	.435	.430	.378	.285	.0			
42	.290	.310	.331	.305	.285	.0		
51	.200	.225	.265	.254	.288	.234	.0	
57	.170	.192	.231	.225	.275	.229	.200	.0
90	.060	.071	.076	.101	.172	.202	.229	.265
120	.0	.0	.010	.045	.124	.194	.245	.285
150			.0	.0	.090	.184	.235	.275
210					.032	.133	.195	.235
270					.0	.096	.155	.195
330						.065	.125	.165
390						.031	.101	.141
450						.0	.078	.118
510							.055	.095
570							.032	.072
690							.0	.0

Table 7. Advance and recession data for CRC border #4, 8/15/79.

	observed			computed		
distance	advance	reces.	opport.	advance	reces.	opport.
(ft)		(min)				
0	0	110	110	0	108	108
50	1	120	119	1	109.4	108.4
150	8	130	122	8	124.5	116.5
250	19	150	131	19	144.1	125.1
350	35	240	205	35	243.1	208.1
450	42	445	403	42	444.7	402.7
550	51	630	579	51	653.5	602.5
620	57	690	633	57	690	633

Table 8. Profile data for CRC border #6, 8/15/79.

Station distance (ft)	0	50	150	250	350	450	550	620
Station elevation (ft)	.85	.80	.70	.56	.47	.42	.33	.26
Time (min)			station depths (ft)					
1	.090	.0						
8	.310	.292	.0					
17	.400	.387	.293	.0				
26	.425	.421	.378	.267	.0			
35	.180	.203	.262	.287	.258	.0		
49	.050	.088	.161	.221	.245	.171	.0	
61	.010	.044	.105	.173	.205	.165	.178	.0
75	.0	.028	.062	.127	.156	.143	.215	.285
90		.0	.020	.085	.126	.135	.233	.305
120			.0	.020	.075	.120	.255	.325
150				.0	.043	.100	.236	.306
210					.0	.068	.203	.273
270						.041	.189	.259
330						.015	.149	.219
390						.0	.121	.191
450							.093	.163
510							.065	.135
570							.037	.107
630							.010	.080
800							.0	.0

Table 9. Advance and recession data for CRC border #6, 8/15/79.

	observed			computed		
distance	advance	reces.	opport.	advance	reces.	opport.
(ft)		(min)				
0	0	64	64	0	64	64
50	1	85	84	1	90	89
150	8	100	92	8	97.1	89.1
250	17	130	113	17	129.2	112.2
350	26	220	194	26	190.3	164.3
450	35	360	325	35	364.6	329.6
550	49	650	601	49	652.2	603.2
620	61	800	739	61	800	739

Table 10. Profile data for CRC border #7, 8/15/79.

Station distance (ft)	0	50	150	250	350	450	550	620
Station elevation (ft)	.82	.78	.70	.64	.61	.57	.54	.53
Time (min)	station depths (ft)							
1	.110	.0						
10	.340	.298	.0					
21	.420	.395	.303	.0				
34	.450	.434	.395	.292	.0			
47	.390	.405	.418	.388	.260	.0		
64	.180	.210	.265	.307	.256	.187	.0	
77	.107	.142	.213	.253	.220	.180	.114	.0
90	.073	.106	.173	.219	.189	.160	.137	.130
105	.037	.069	.132	.164	.158	.149	.161	.171
125	.018	.029	.091	.118	.130	.140	.168	.178
165	.0	.0	.005	.045	.075	.112	.145	.155
225			.0	.015	.045	.085	.115	.125
285				.0	.015	.055	.085	.095
345					.0	.025	.055	.065
405						.0	.025	.035
475							.0	.0

Table 11. Advance and recession data for CRC border 7, 8/15/79.

	observed			computed		
distance	advance	reces.	opport.	advance	reces.	opport.
(ft)		(min)				
0	0	150	150	0	143.9	143.9
50	1	160	159	1	139.5	138.5
150	10	180	170	10	167.3	157.3
250	21	245	224	21	255	234
350	34	324	290	34	315	281
450	47	366	319	47	395	348
550	64	432	368	64	455	391
620	77	475	398	77	475	398

Table 12. Profile data for CRC border #9, 8/15/79.

Station distance (ft)	0	50	150	250	350	450	550	620
Station elevation (ft)	.79	.76	.68	.65	.60	.55	.53	.52
Time (min)	station depths (ft)							
3	.160	.0						
10	.450	.410	.0					
19	.520	.487	.346	.0				
30	.450	.453	.435	.272	.0			
43	.270	.283	.315	.283	.233	.0		
67	.110	.128	.180	.179	.175	.160	.0	
89	.505	.075	.115	.111	.132	.137	.096	.0
120	.025	.042	.059	.063	.084	.100	.103	.100
180	.0	.0	.0	.0	.0	.051	.092	.102
240						.0	.056	.066
300							.021	.031
360							.0	.0

Table 13. Advance and recession data for CRC border #9, 8/15/79.

	observed			computed		
distance	advance	reces.	opport.	advance	reces.	opport.
(ft)	(min)					
0	0	165	165	0	151	151
50	3	168	165	3	159.5	156.5
150	10	175	165	10	152.7	142.7
250	19	180	161	19	160.7	141.7
350	30	180	150	30	174.3	144.3
450	43	230	187	43	240	197
550	67	340	273	67	336	269
620	89	360	271	89	353.1	264.1

Table 14. Kostiakov infiltration constants for CRC border irrigation trials, 8/15/79. Where $Z = k\ t^a$, Z = cumulative infiltrated depth (hrs), t = opportunity time (hrs), k = constant (in/hr^a), and a = exponent.

	Borders					
	1	3	4	6	7	9
Volume balance						
k	1.525	2.120	1.105	1.887	1.367	1.994
k (adj)*	1.53		1.15		1.25	
a	0.511	0.303	0.644	0.268	0.683	0.354
Volume balance (t > 1 hr)						
k	1.49	1.770	1.15	1.590	1.614	1.814
k (adj)*	1.50		1.19		1.60	
a	0.520	0.449	0.623	0.483	0.515	0.493
Ring Data						
k	1.31		2.63		1.86	
k (adj)*	1.58		1.21		1.56	
a	0.496		0.614		0.532	

* - adjusted to give volume balance at end of irrigation.

Table 15. Roughness values computed for data from CRC, 1979 experiments.

			Manning Roughness Values		
Border #	Slope	Unit Flow Rate	Avg. of Medians	Median of Medians	Range of Medians
		(cfs/ft)			
1	0.000	0.0675	0.183	0.192	0.283 - 0.074
3		0.1016	0.125	0.109	0.203 - 0.071
4	0.001	0.0678	0.147	0.120	0.205 - 0.087
6		0.1016	0.133	0.124	0.161 - 0.095
7	0.0005	0.0677	0.177	0.177	0.237 - 0.132
9		0.1016	0.145	0.118	0.203 - 0.100

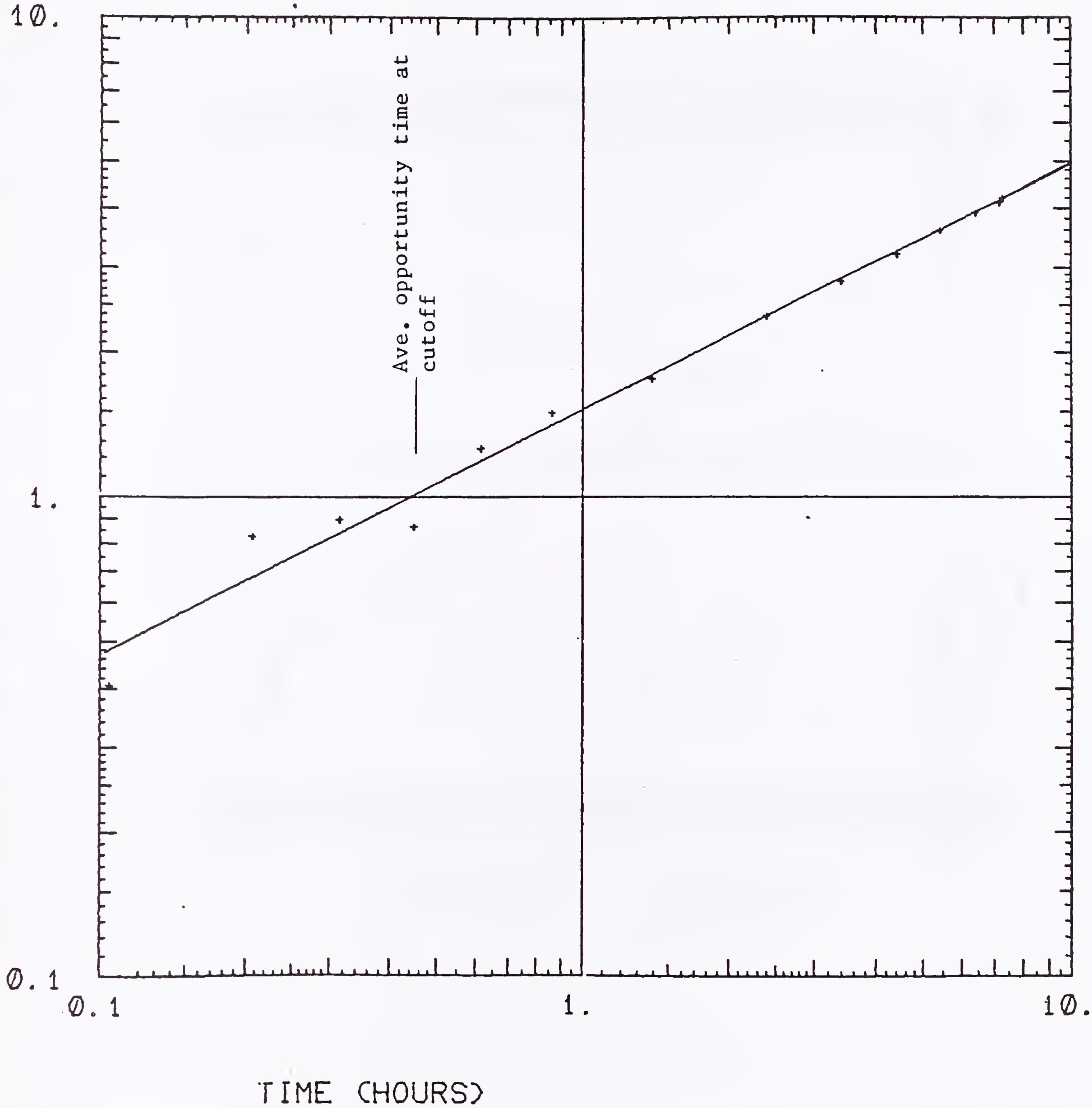


Figure 1. Results of volume balance model for CRC border #1, 8/15/79.

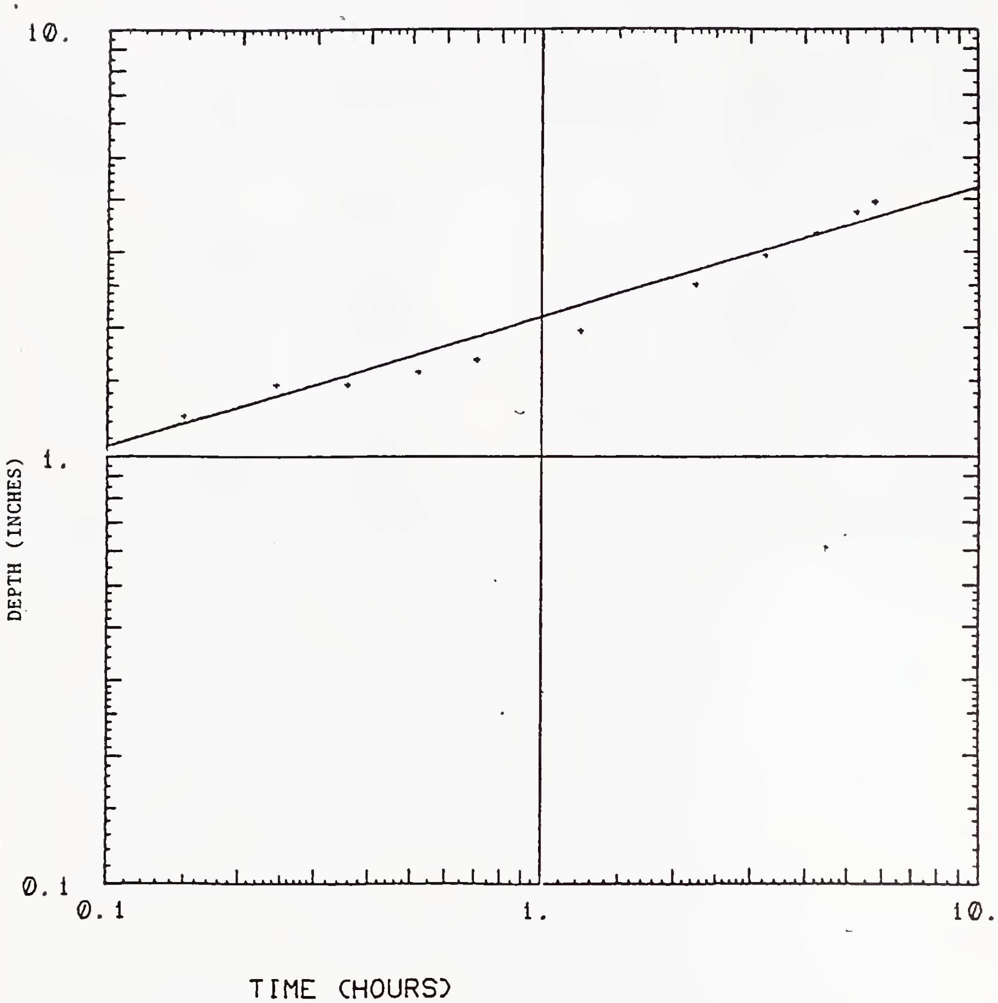


Figure 2. Results of volume balance model for CRC border #3, 8/15/79.

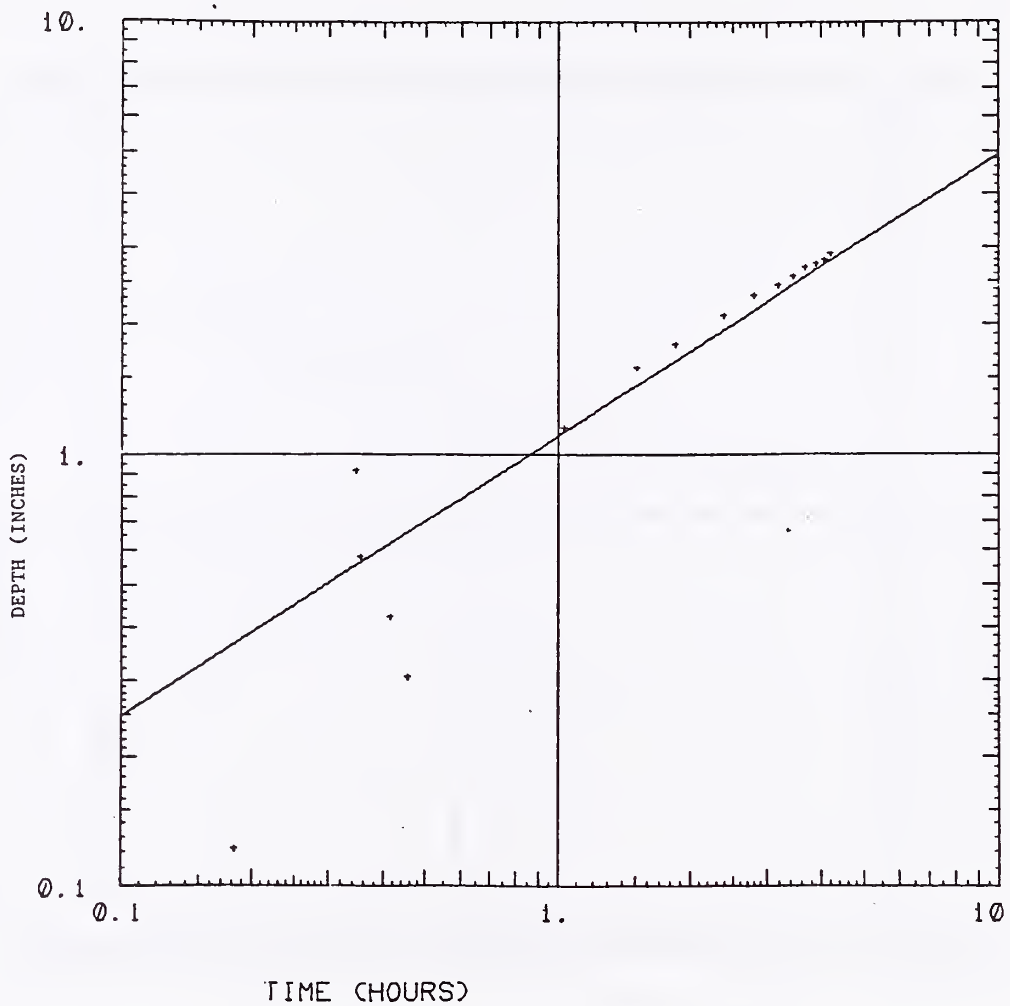


Figure 3. Results of volume balance model for CRC border #4, 8/15/79.

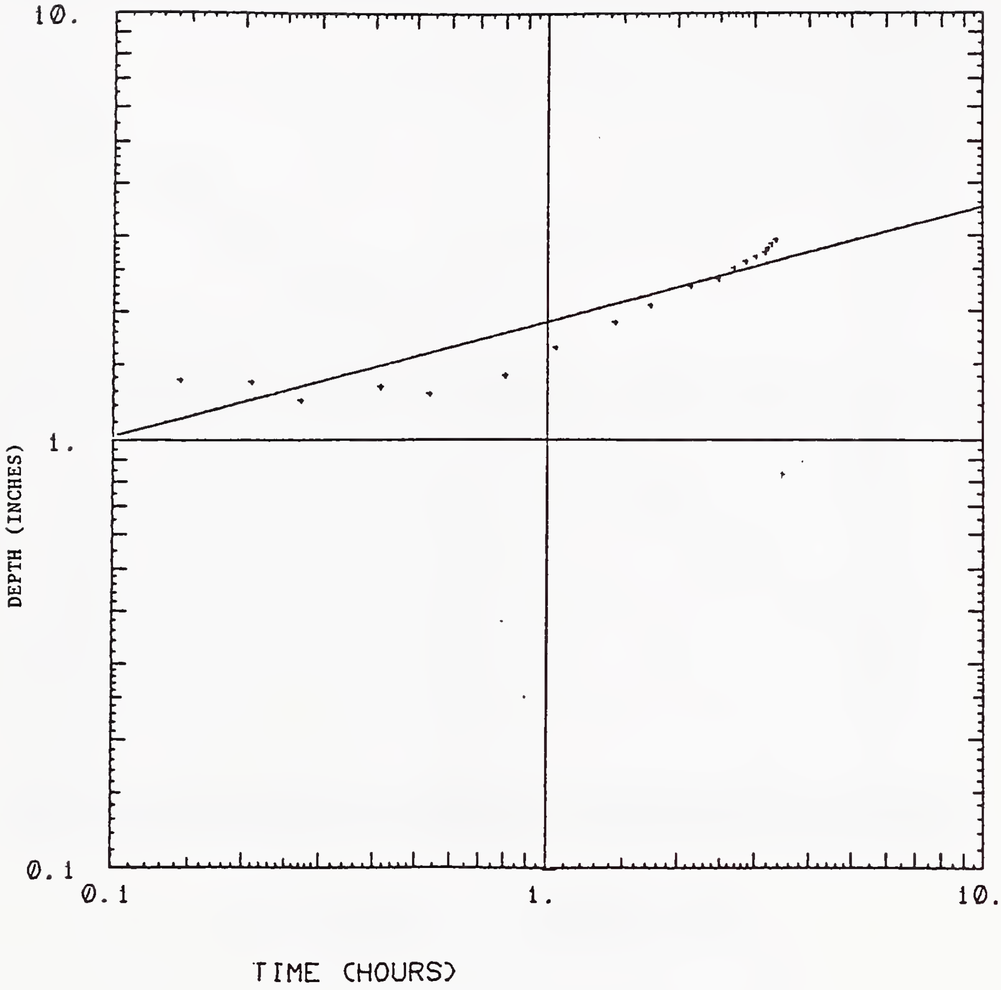


Figure 4. Results of volume balance model for CRC border #6, 8/15/79.

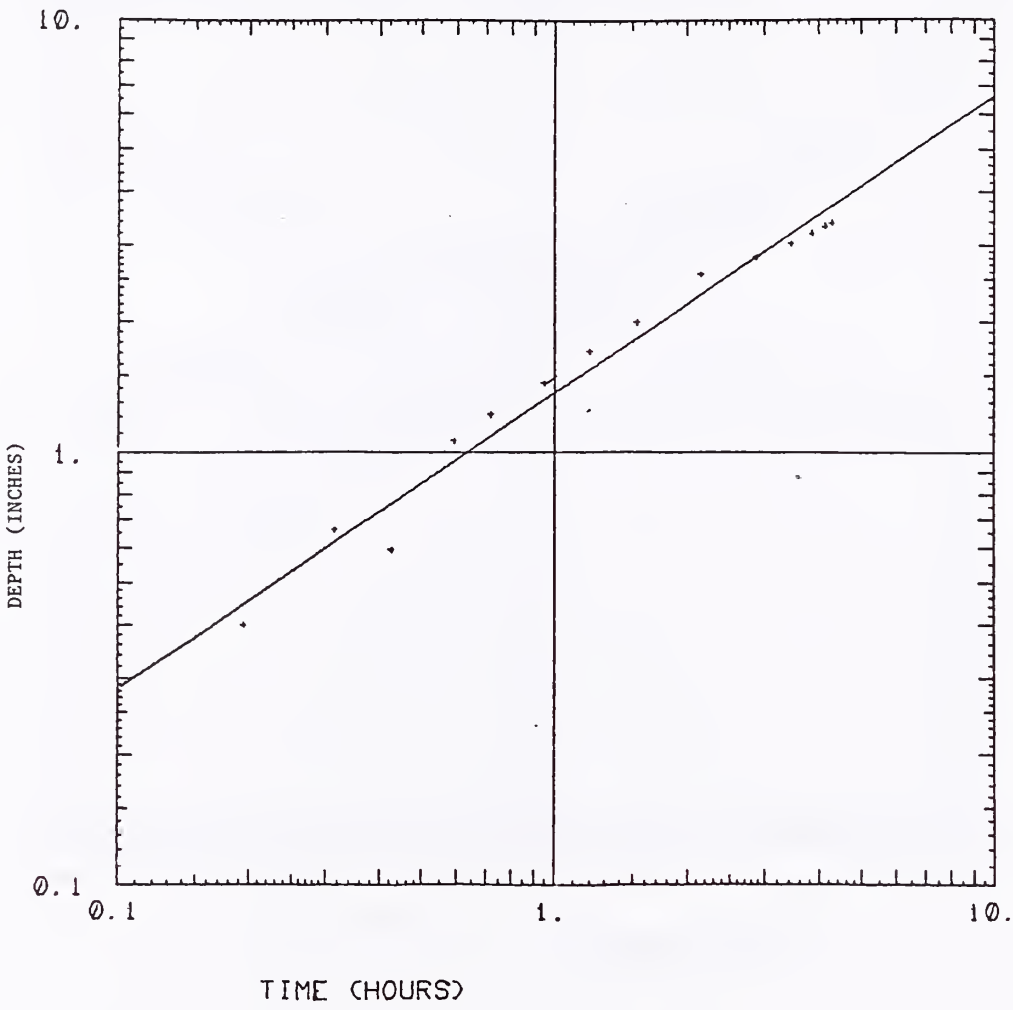


Figure 5. Results of volume balance model for CRC border #7, 8/15/79.

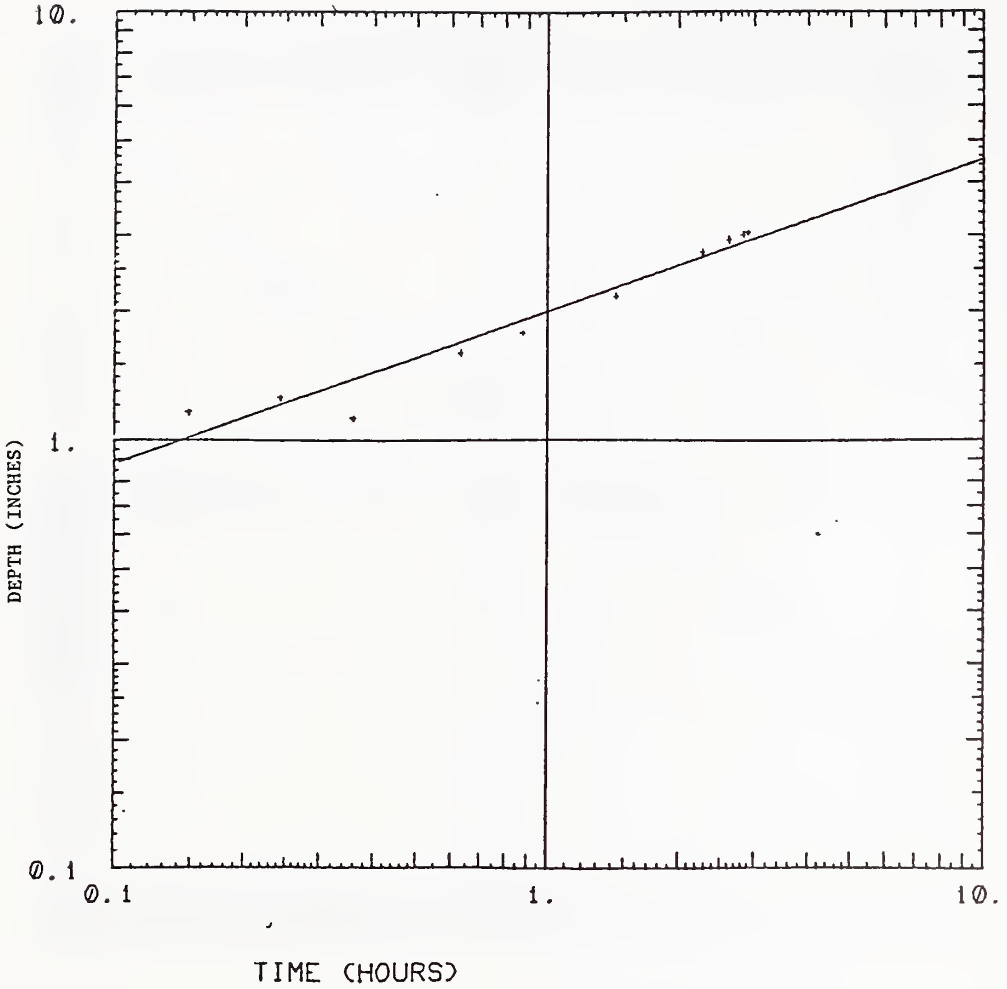


Figure 6. Results of volume balance model for CRC border #9, 8/15/79.

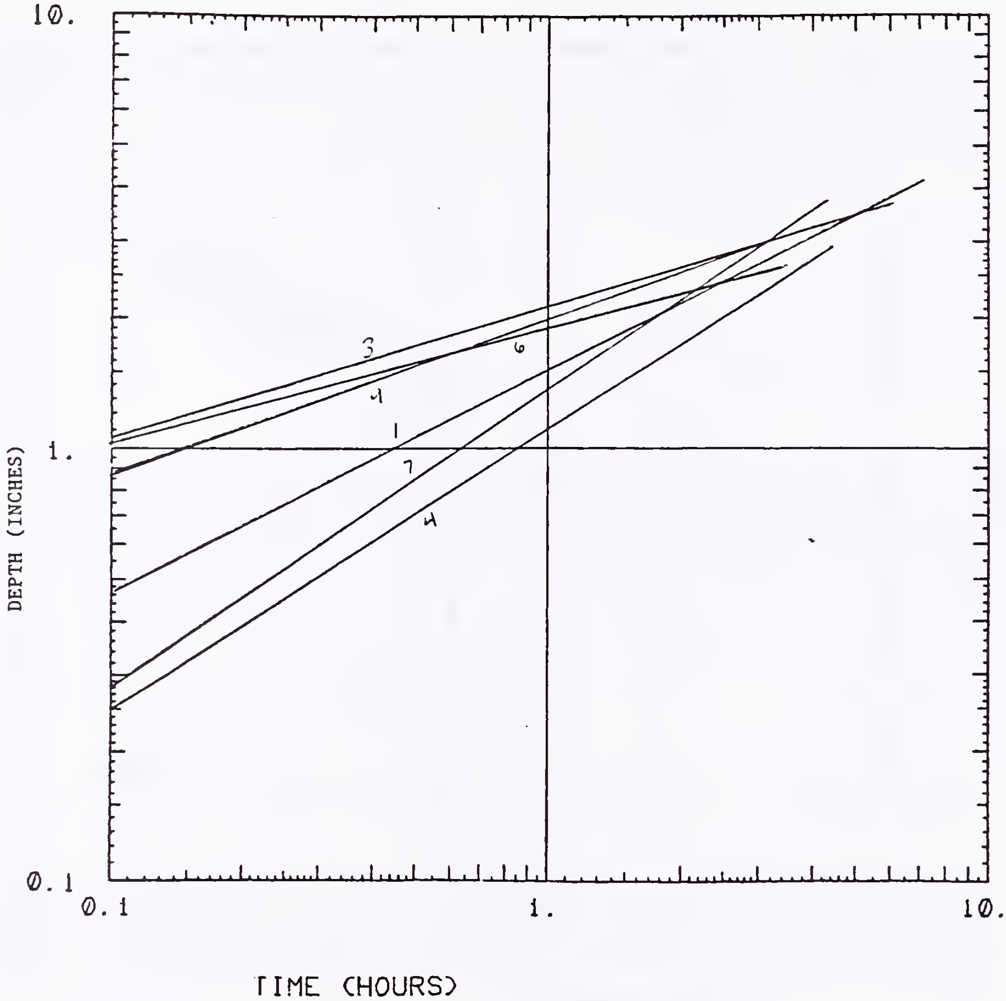


Figure 7. Best fit equations to volume balance data for CRC field trials, 8/15/79.

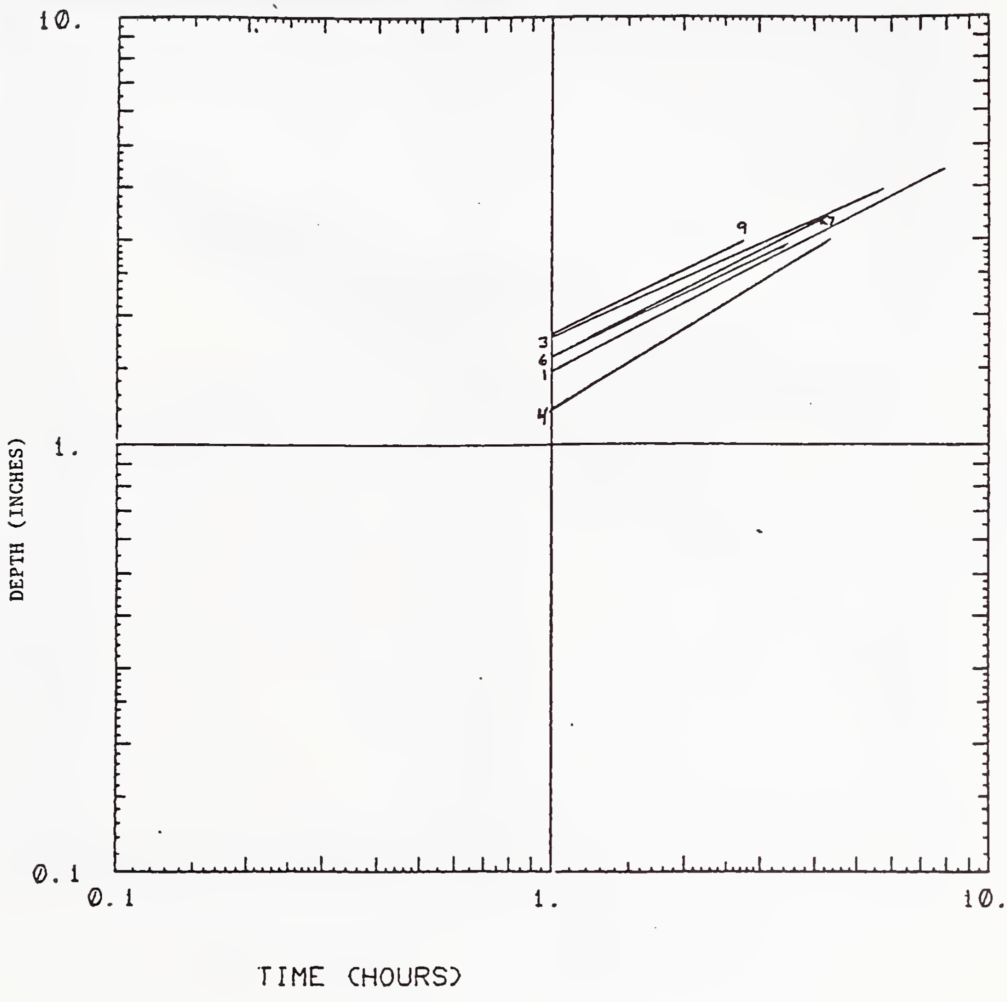


Figure 8. Best fit equations to volume balance data for times greater than 1 hour for CRC field trials, 8/15/79.

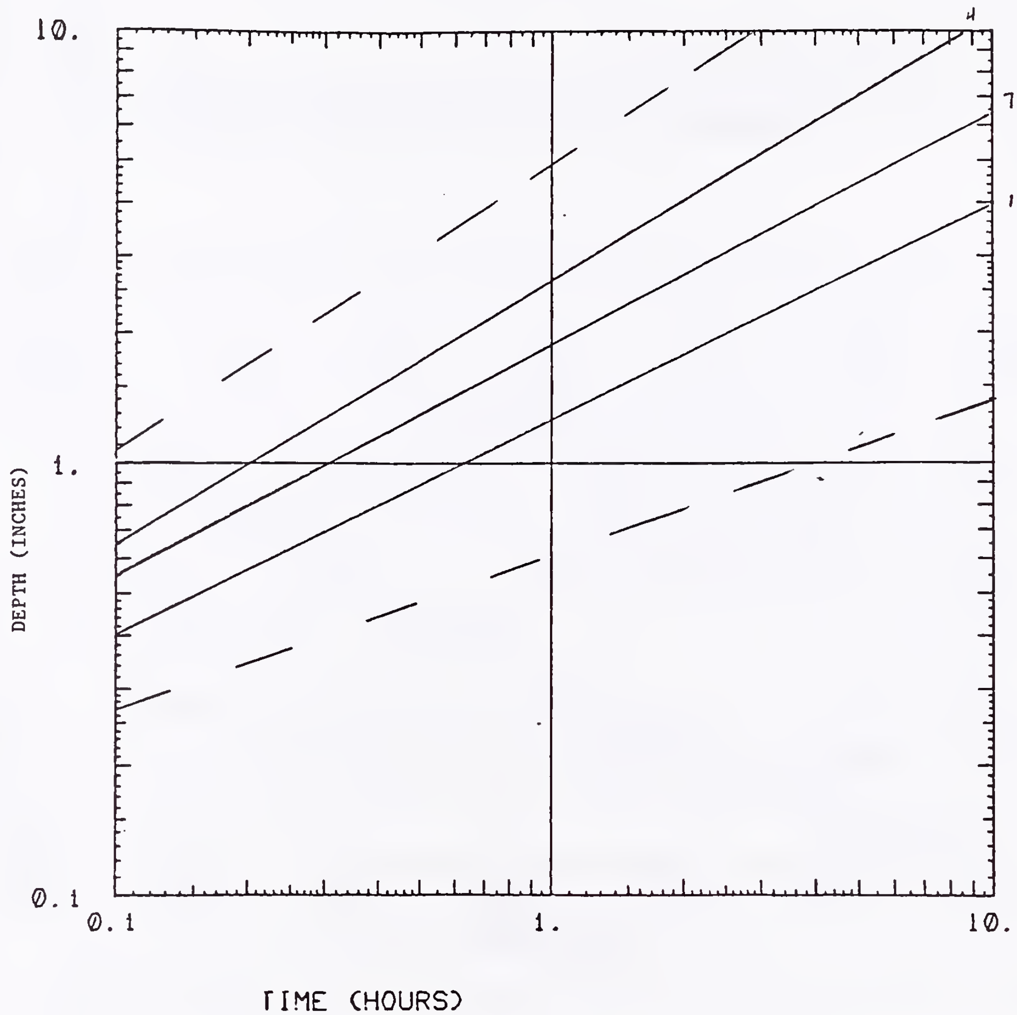


Figure 9. Best fit equations to ring infiltration data plus bounds on data scatter for CRC field trials, 8/15/79.

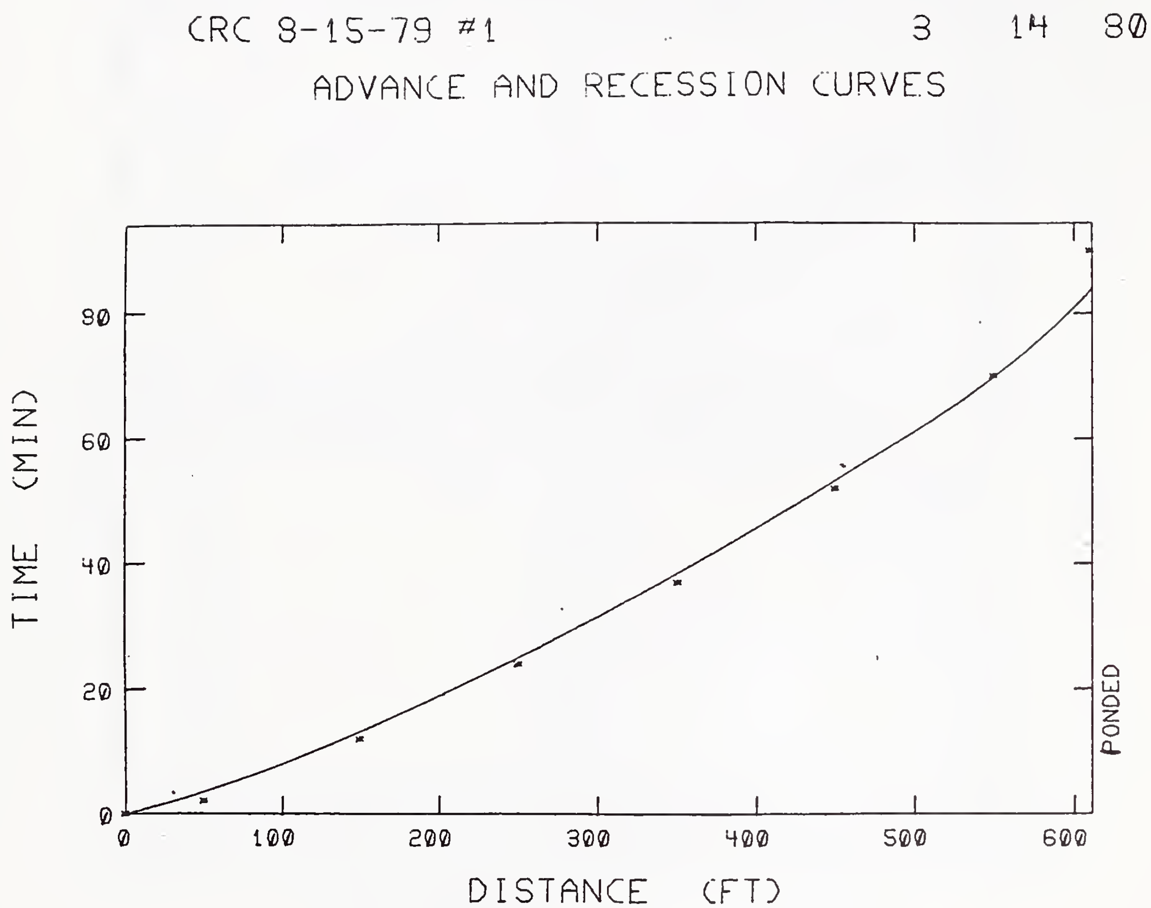
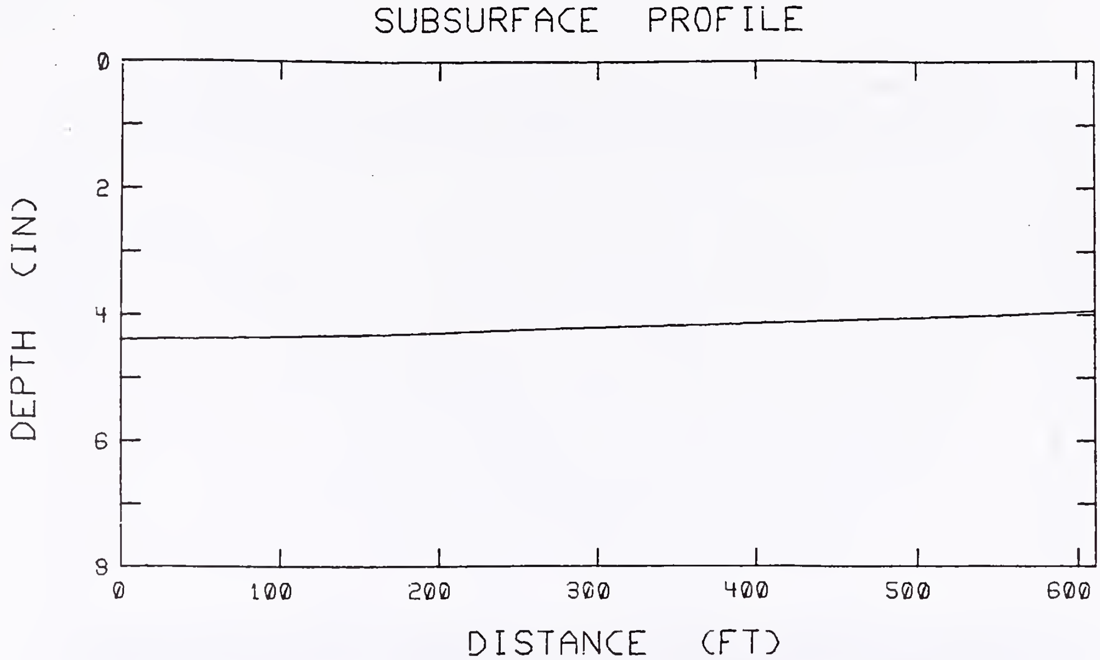


Figure 10. Advance and recession curves for CRC border #1, 8/15/79. Infiltration constants k = 1.525 in/hr^a, a = 0.511.



FLOW RATE 0.0675 CFS/FT INFILTRATION CONSTANT 1.525 IN/HR**A

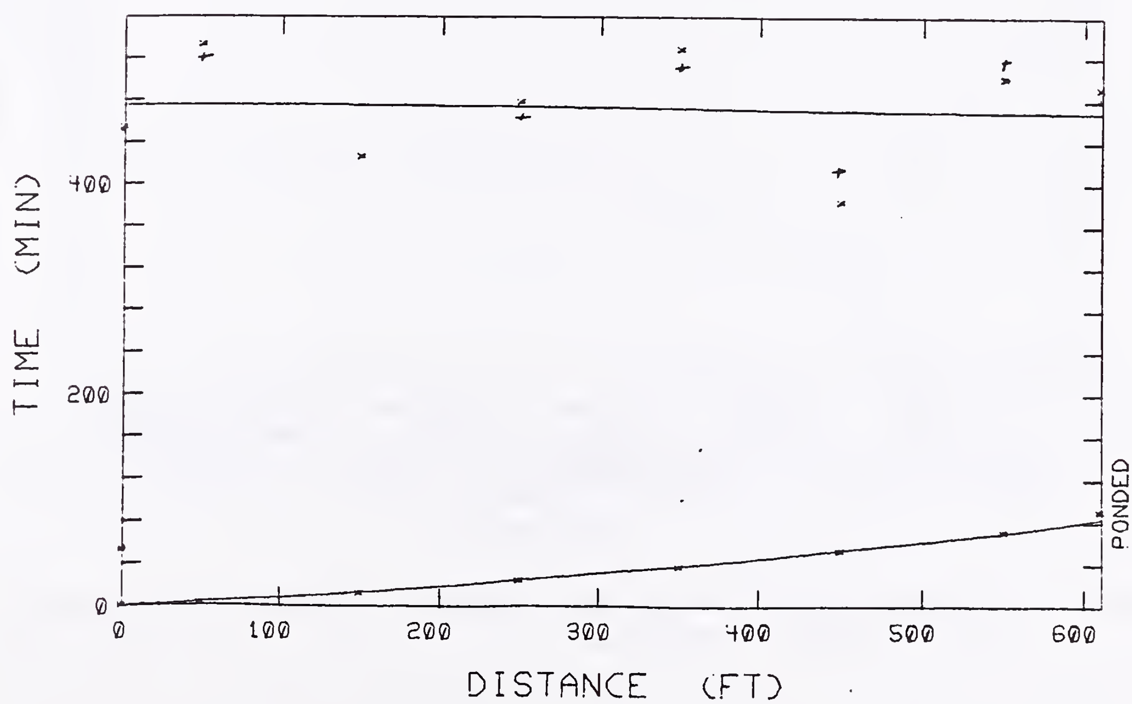
BOTTOM SLOPE 0.000 % INFILTRATION POWER 0.511

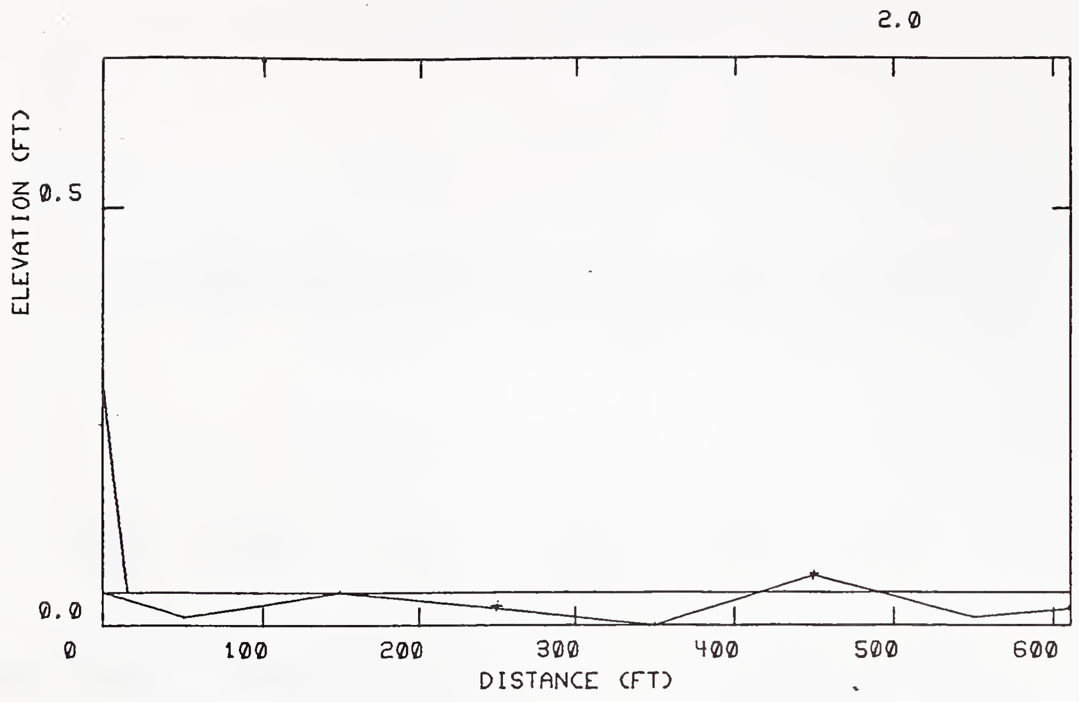
MANNING N 0.183 FINAL INFILTRATION RATE 0.000 IN/HR

APPLICATION TIME 53.0 MIN.

CRC 8-15-79 #1 3 14 80

ADVANCE AND RECESSION CURVES





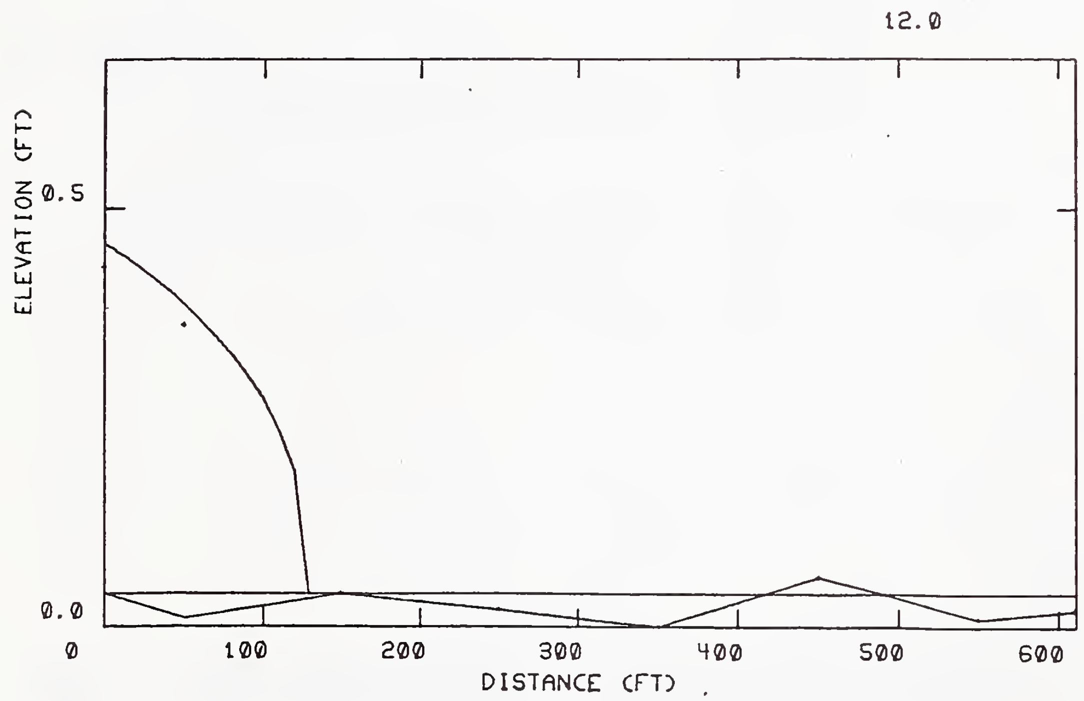
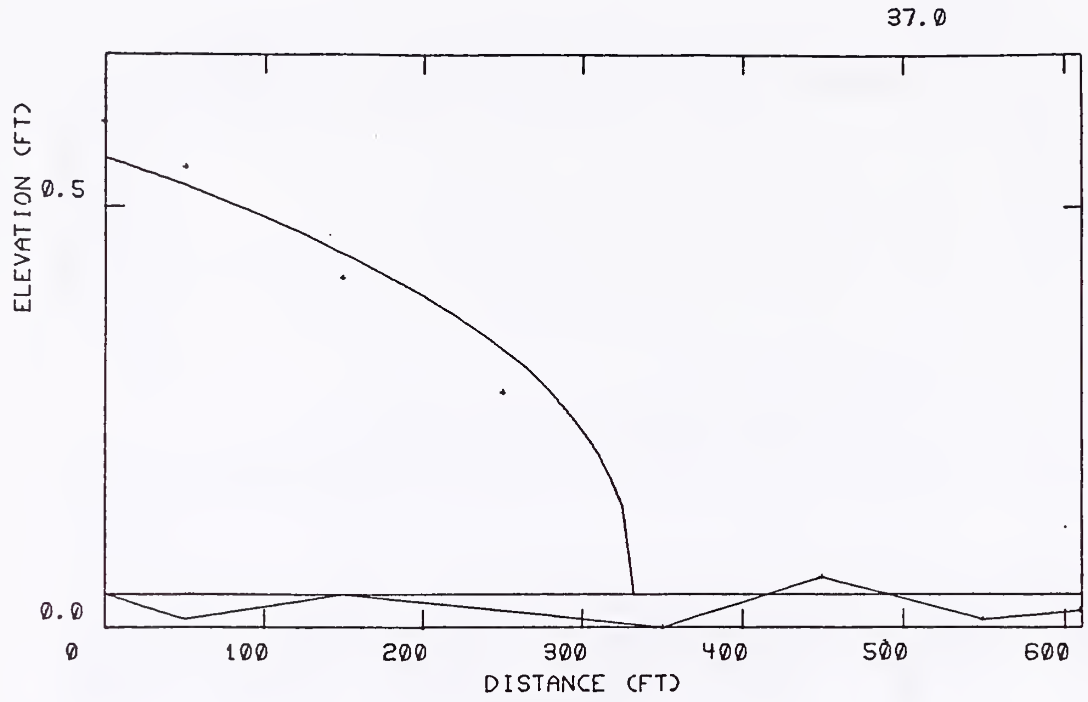
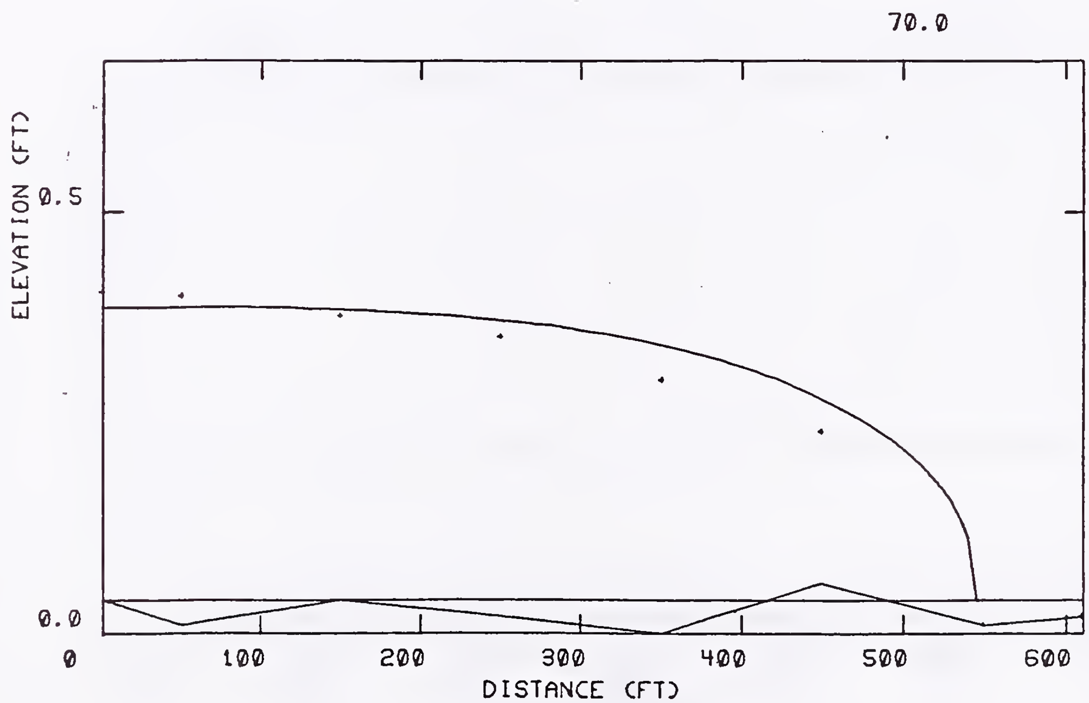
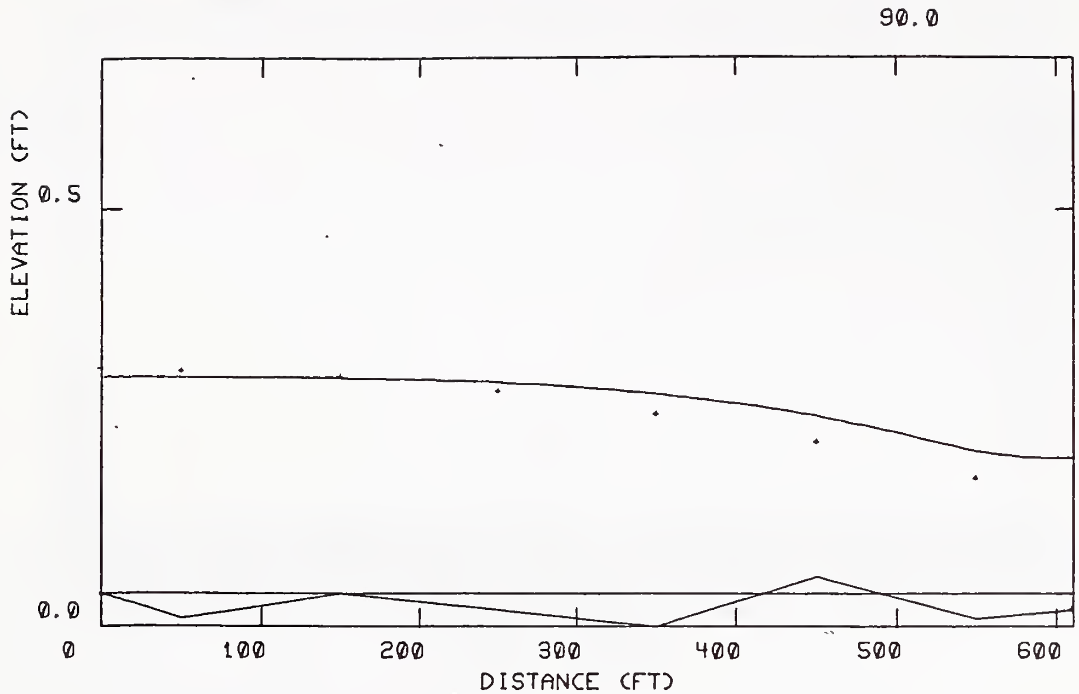
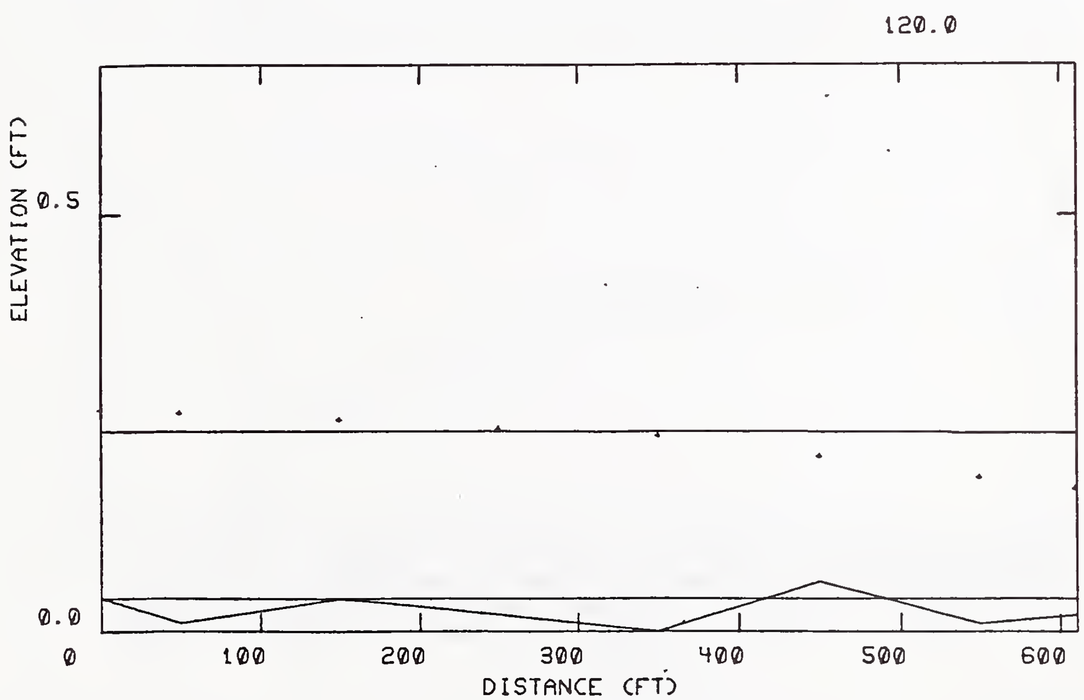


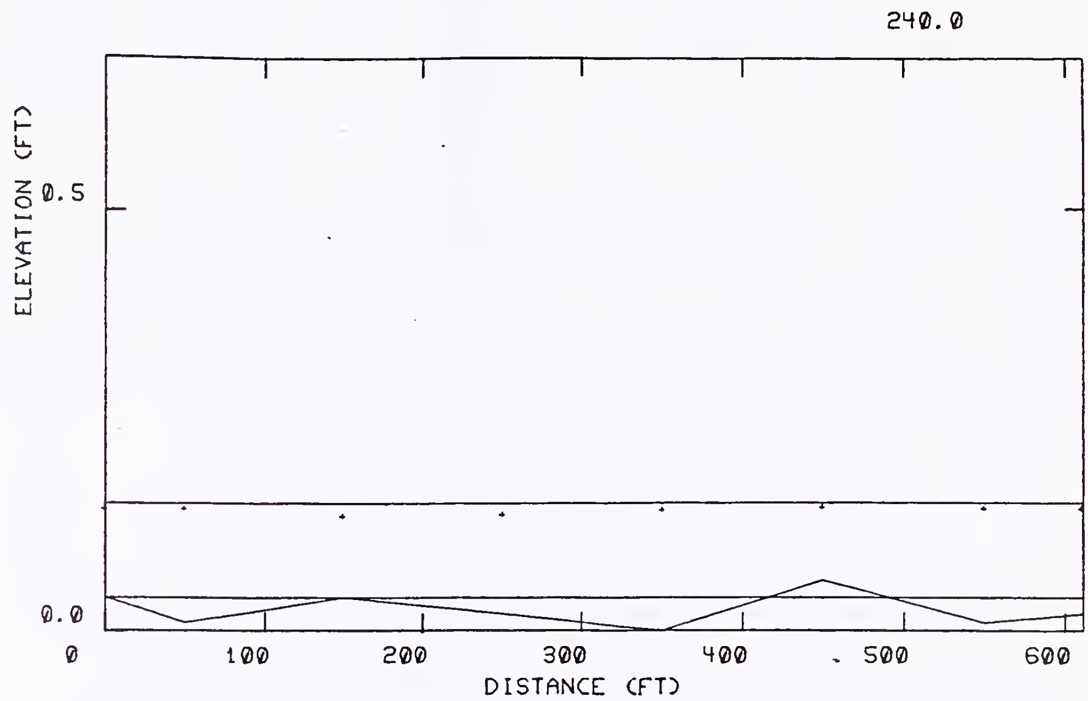
Figure 11. Profiles for CRC border #1, 8/15/79. Infiltration constants k = 1.525 in/hr^{a}, a = 0.511.

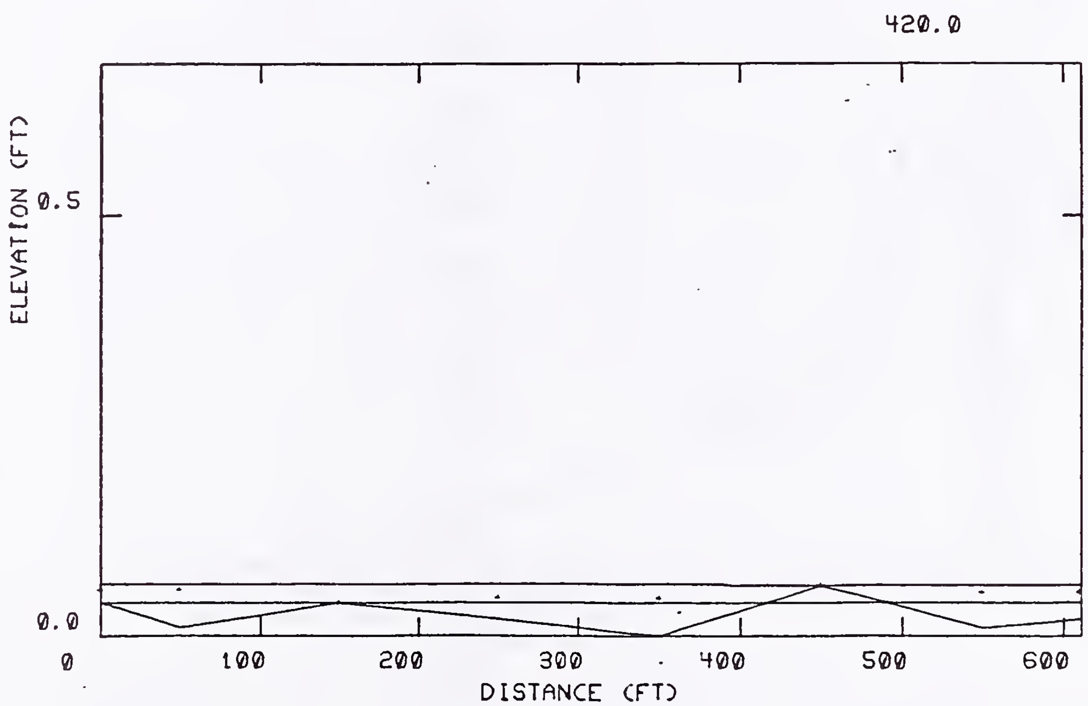

37.0
ELEVATION (FT)
0.5
0.0
0
100
200
300
400
500
600
DISTANCE (FT)

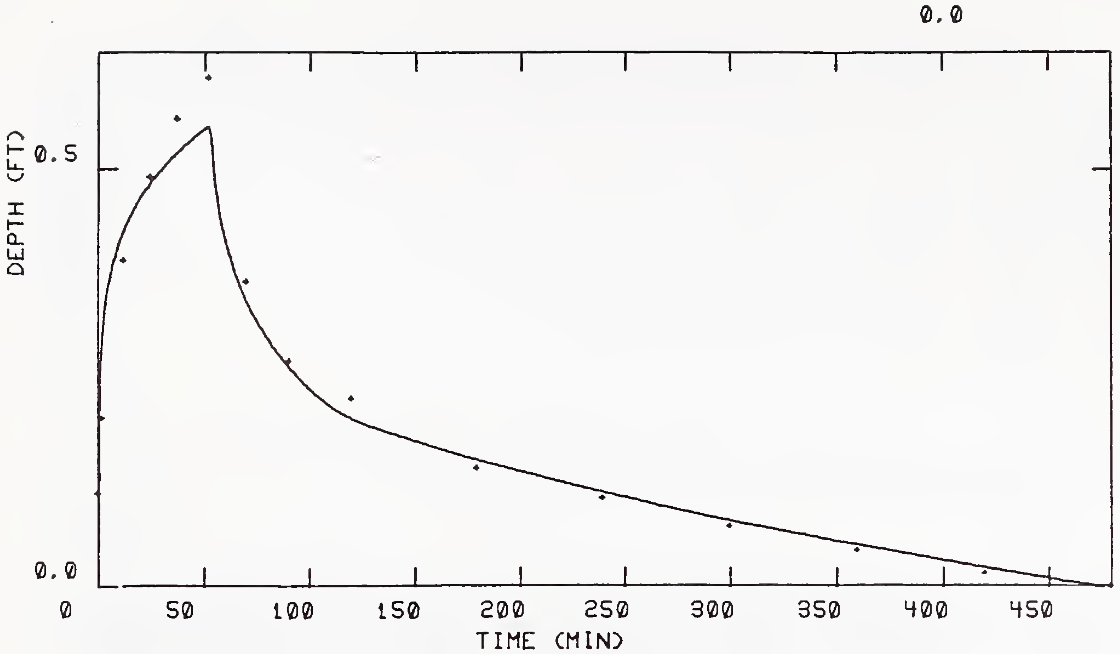

70.0
ELEVATION (FT)
0.5
0.0
0
100
200
300
400
500
600
DISTANCE (FT)


90.0
ELEVATION (FT)
0.5
0.0
0
100
200
300
400
500
600
DISTANCE (FT)


120.0
ELEVATION (FT)
0.5
0.0
0
100
200
300
400
500
600
DISTANCE (FT)


240.0
ELEVATION (FT)
0.5
0.0
0
100
200
300
400
500
600
DISTANCE (FT)


420.0
ELEVATION (FT)
0.5
0.0
0
100
200
300
400
500
600
DISTANCE (FT)



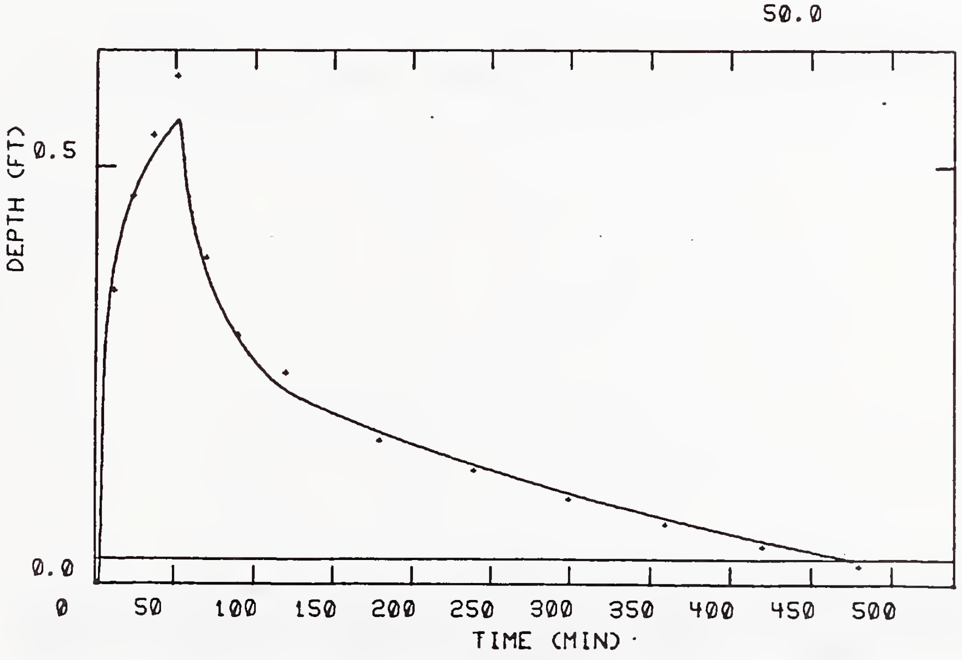
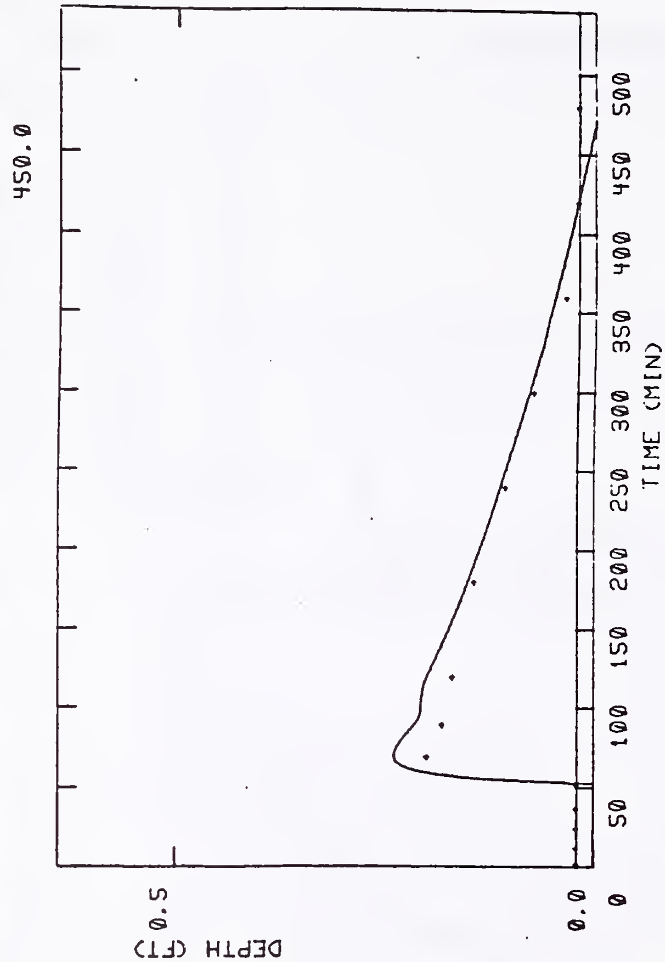
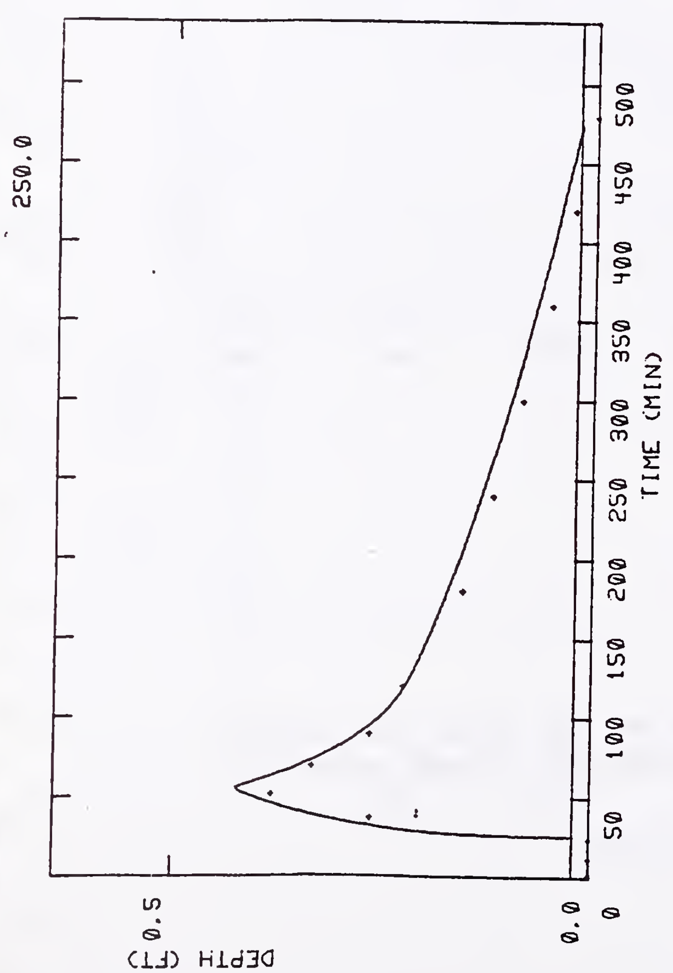
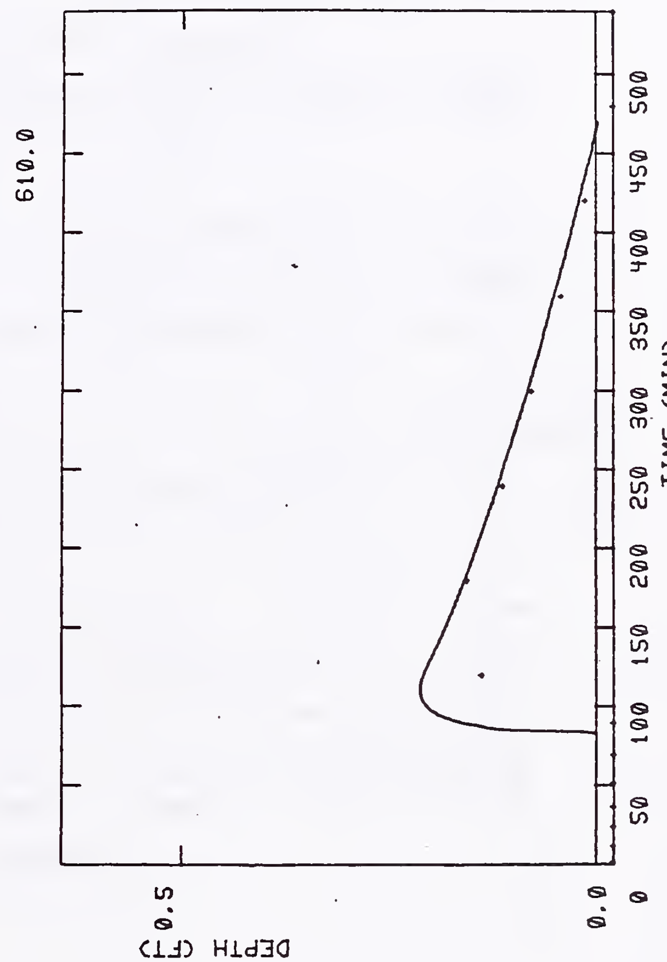


Figure 12. Depth hydrographs for CRC border #1, 8/15/79. Infiltration constants $k = 1.525$ in/hr^a, $a = 0.511$.


450.0
DEPTH (FT)
0.5
0.0
TIME (MIN)
0
50
100
150
200
250
300
350
400
450
500


250.0
DEPTH (FT)
0.5
0.0
TIME (MIN)
0
50
100
150
200
250
300
350
400
450
500


610.0
DEPTH (FT)
0.5
0.0
TIME (MIN)
0
50
100
150
200
250
300
350
400
450
500

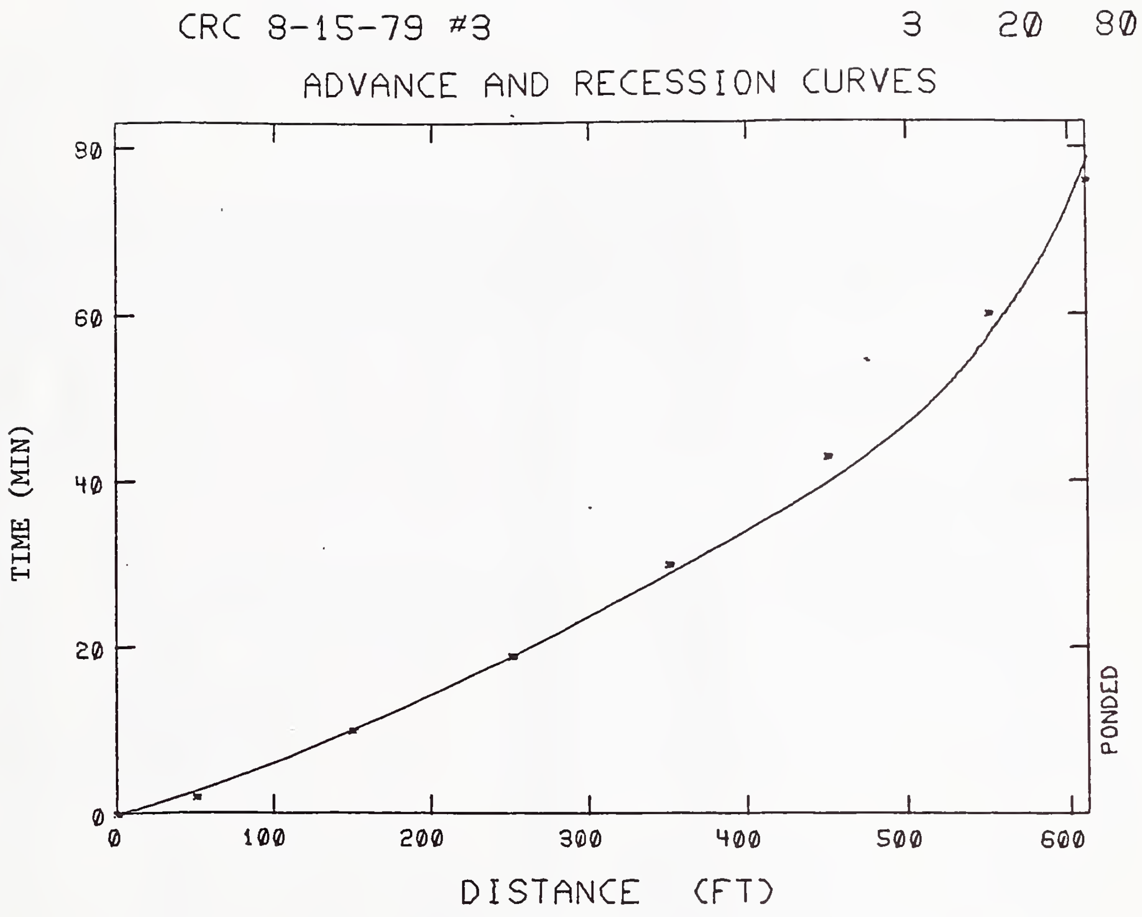
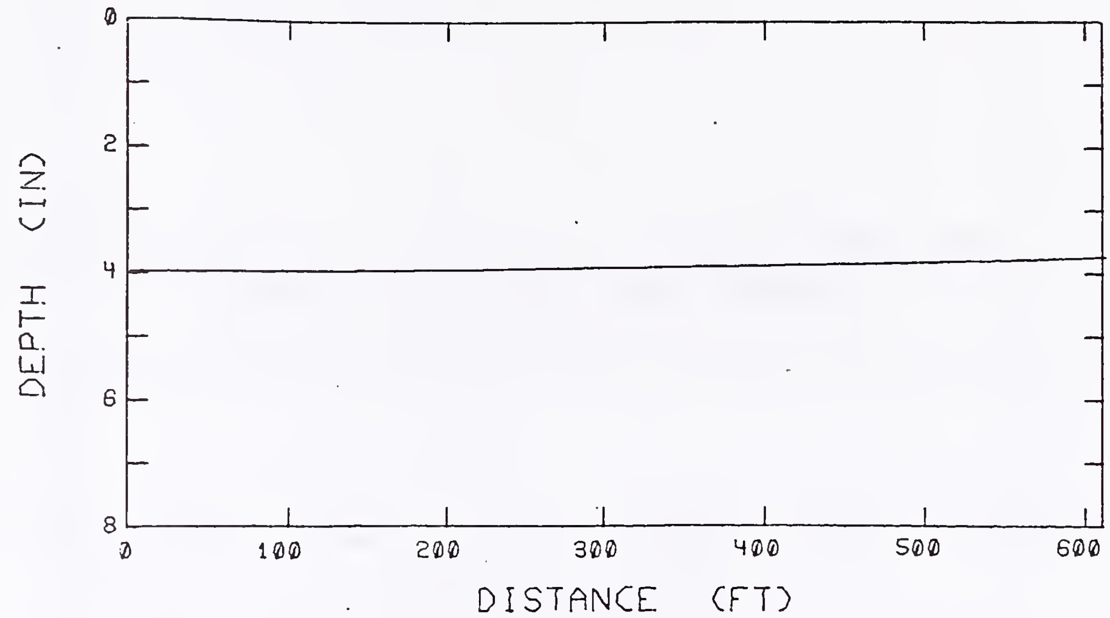


Figure 13. Advance and recession curves for CRC border #3, 8/15/79. Original volume balance constants, k = 2.120 in/hr^a, a = 0.303.

SUBSURFACE PROFILE



FLOW RATE 0.1016 CFS/FT

BOTTOM SLOPE 0.000 %

MANNING N 0.125

APPLICATION TIME 33.0 MIN.

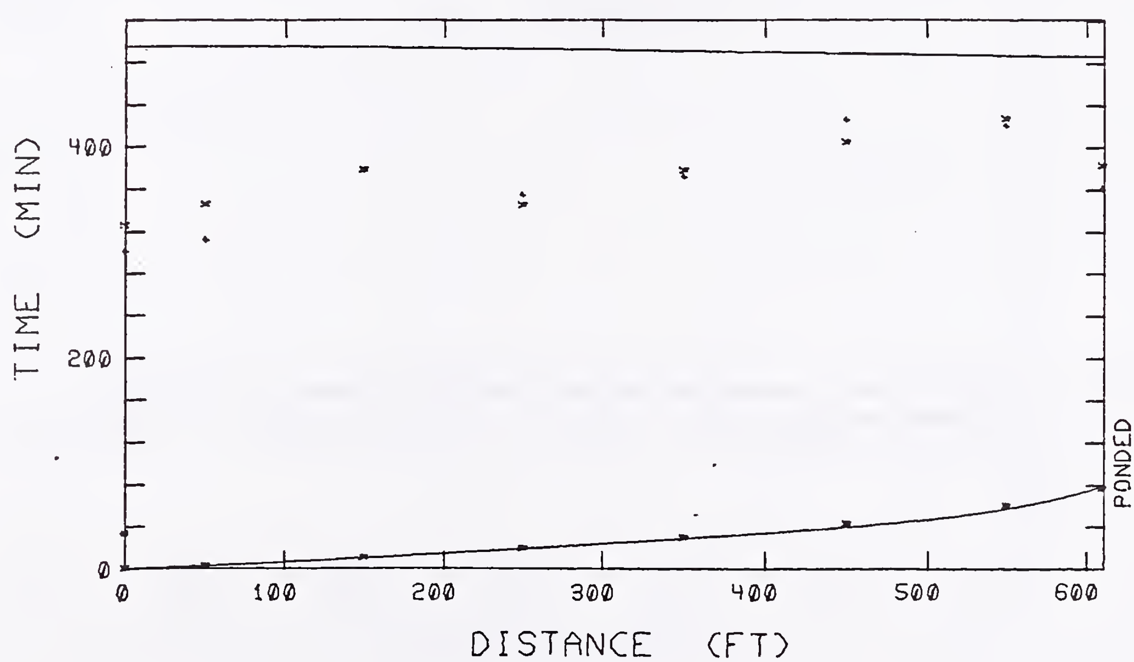
INFILTRATION CONSTANT 2.120 IN/HR**A

INFILTRATION POWER 0.303

FINAL INFILTRATION RATE 0.000 IN/HR

CRC 8-15-79 #3 3 20 80

ADVANCE AND RECESSION CURVES



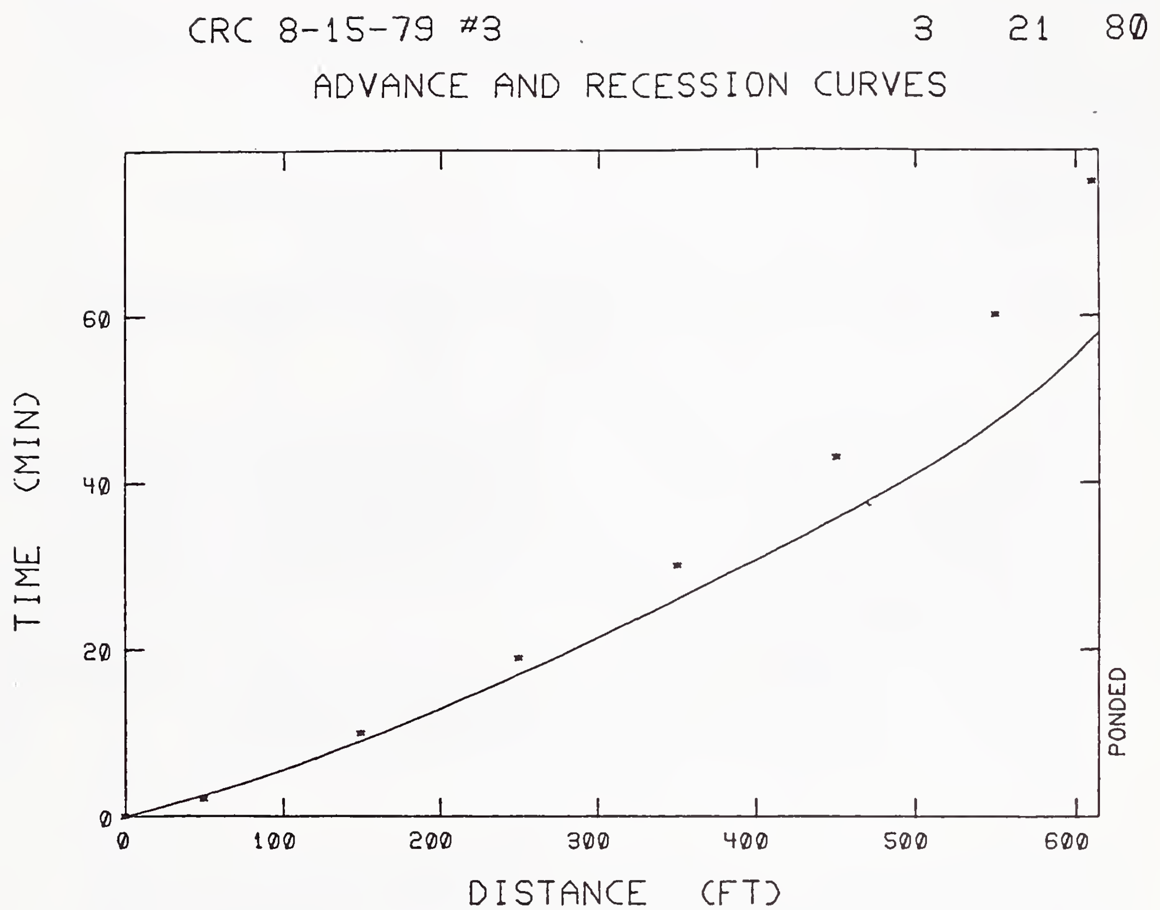
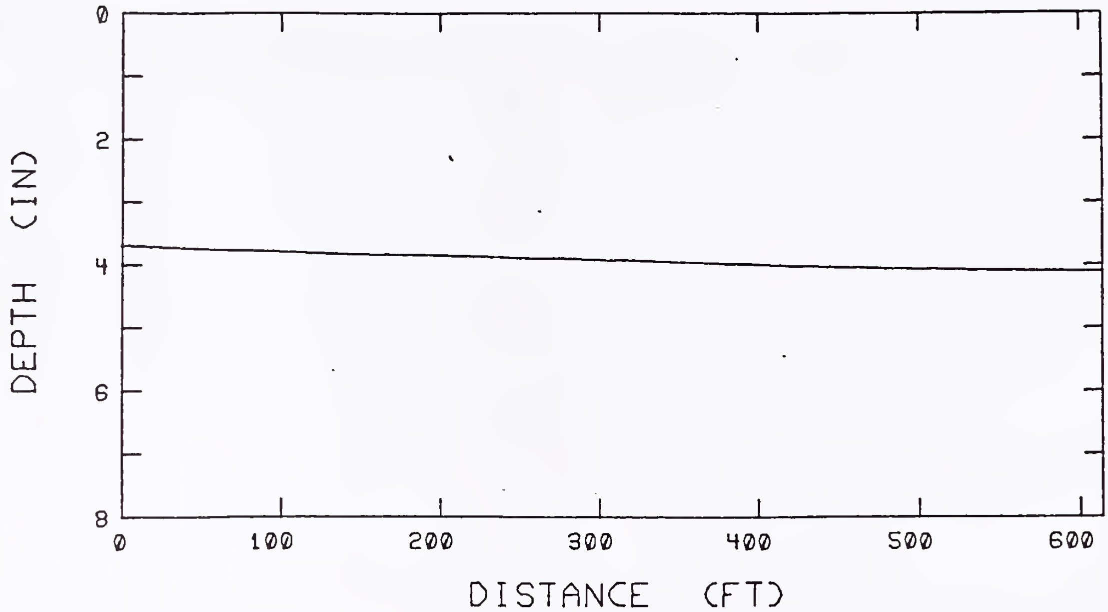


Figure 14. Advance and recession curves for CRC border #3, 8/15/79. Volume balance after 1 hour, k = 1.770 in/hr^a, a = 0.449. (Slope = 0.0001)

SUBSURFACE PROFILE



FLOW RATE 0.1016 CFS/FT

BOTTOM SLOPE 0.010 %

MANNING N 0.125

APPLICATION TIME 33.0 MIN.

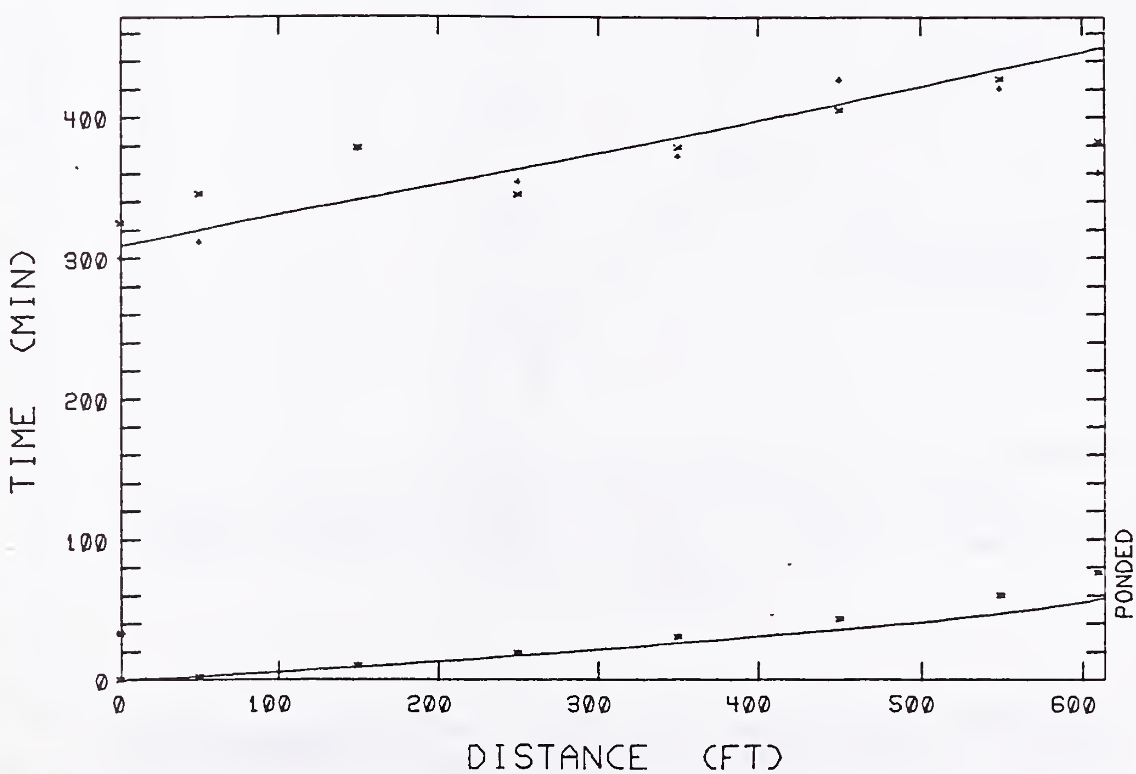
INFILTRATION CONSTANT 1.770 IN/HR**A

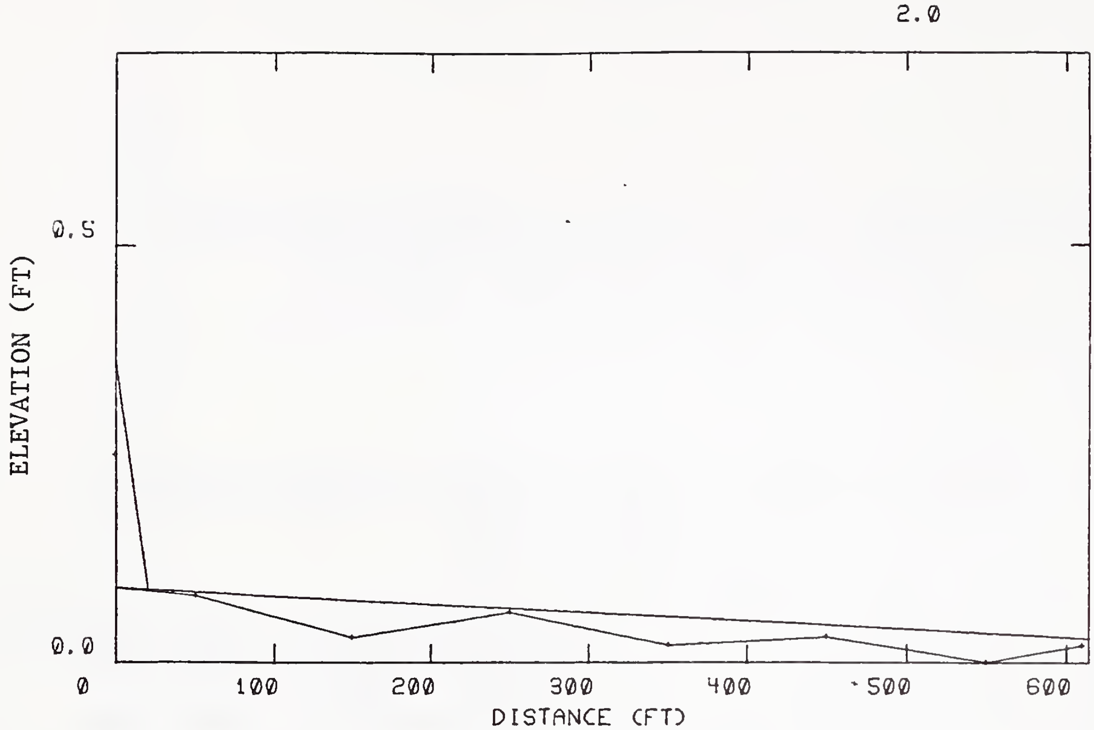
INFILTRATION POWER 0.449

FINAL INFILTRATION RATE 0.000 IN/HR

CRC 8-15-79 #3 3 21 80

ADVANCE AND RECESSION CURVES





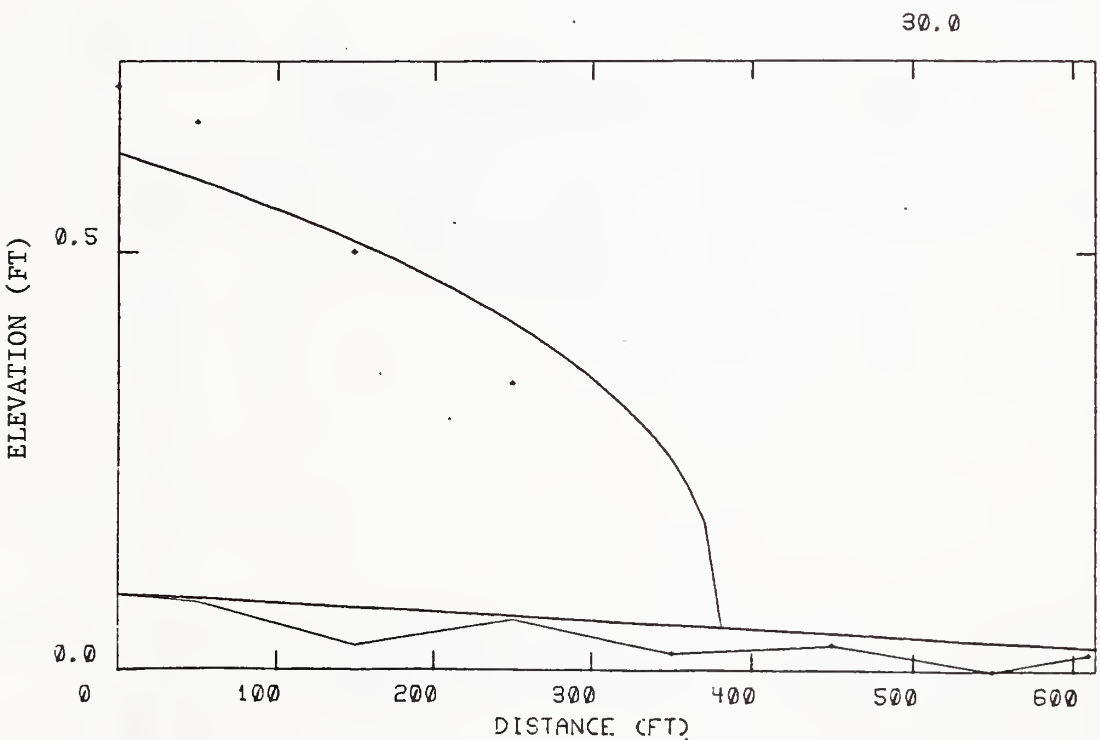
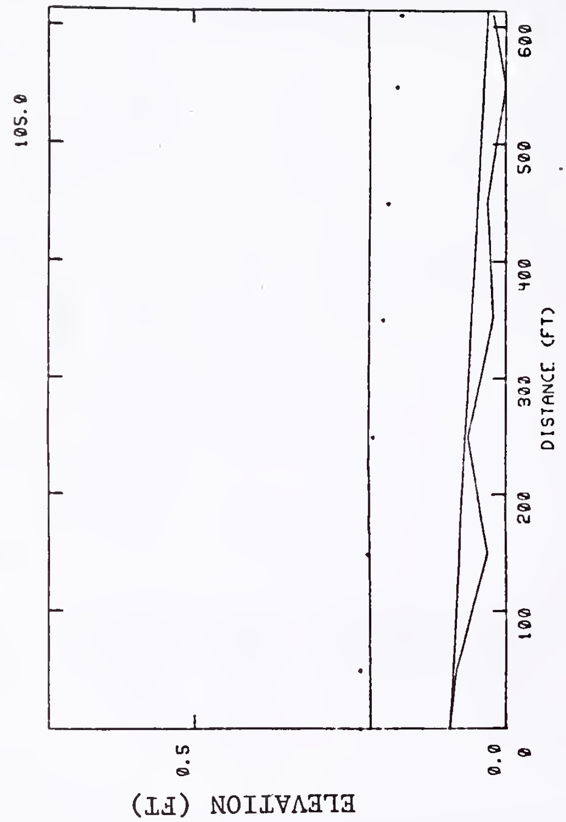
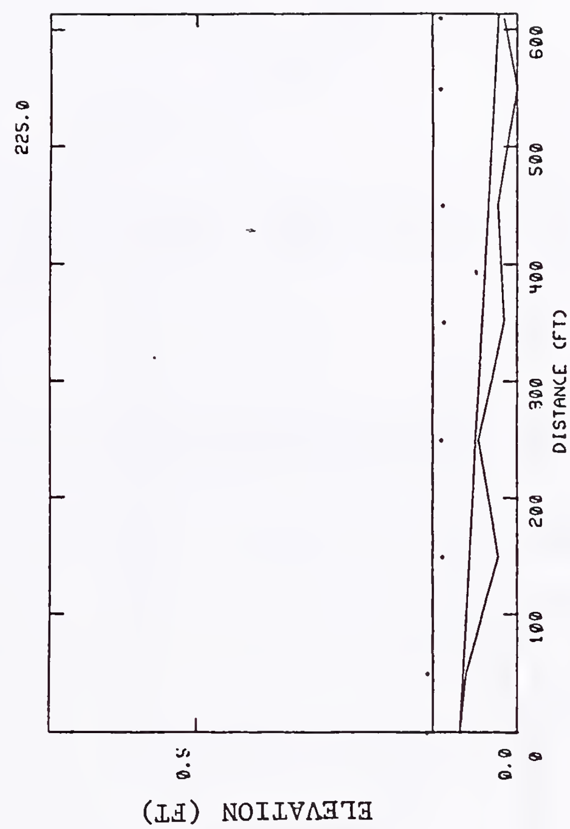
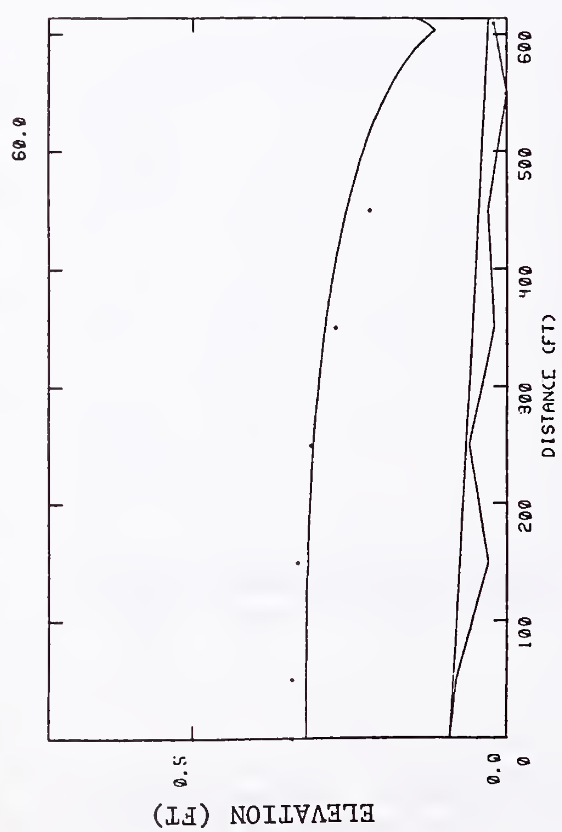


Figure 15. Profiles for CRC border #3, 8/15/79. Volume balance after 1 hour, k = 1.770 in/hr^{a}, a = 0.449. (Slope = 0.0001)


105.0
ELEVATION (FT)
DISTANCE (FT)


225.0
ELEVATION (FT)
DISTANCE (FT)


60.0
ELEVATION (FT)
DISTANCE (FT)

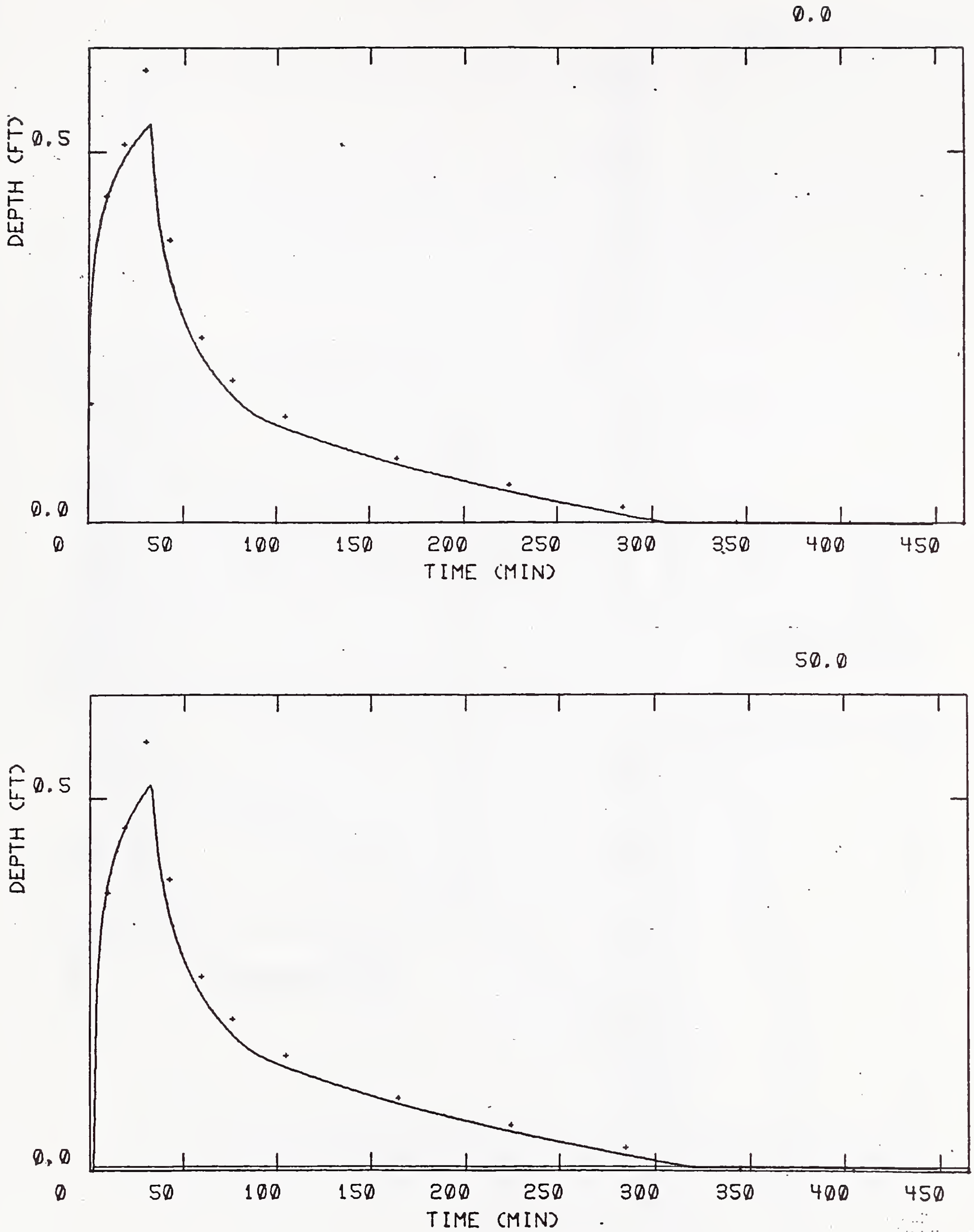
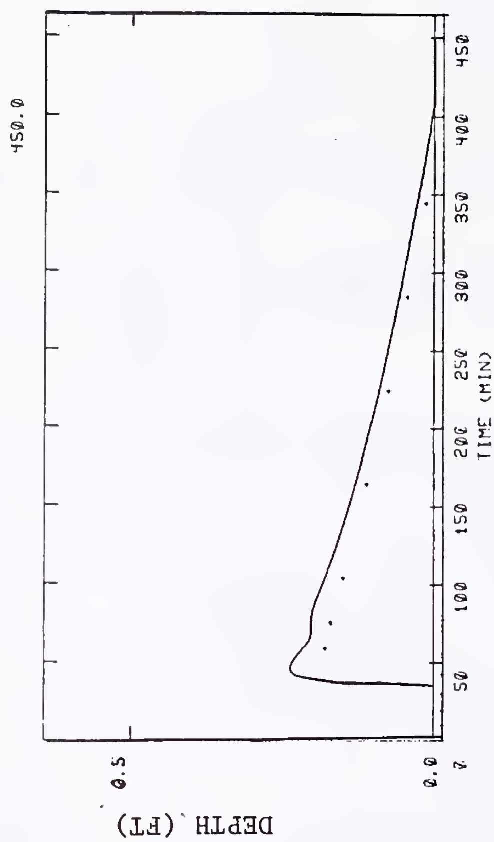
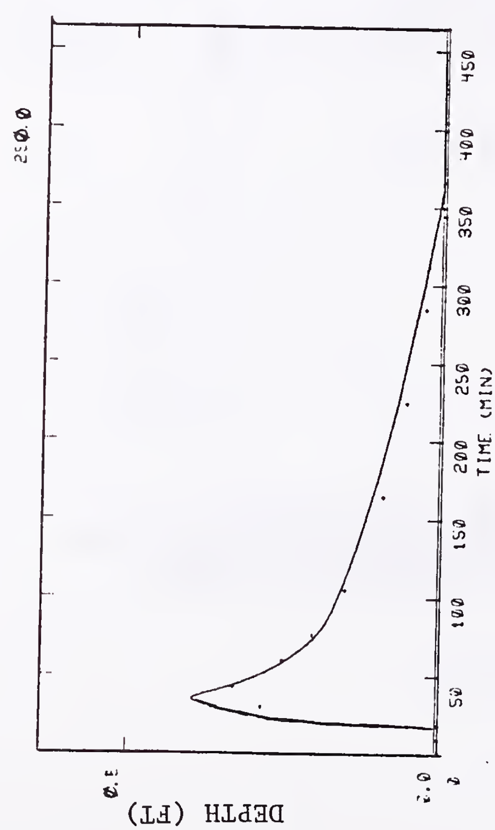
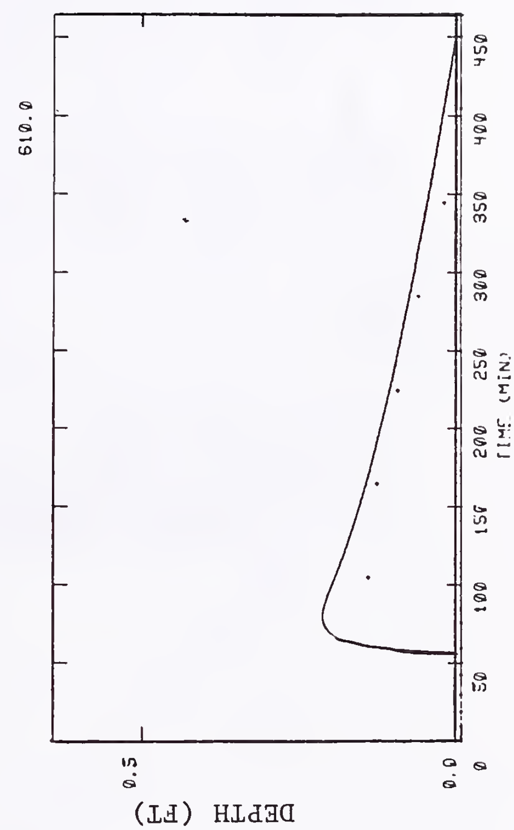


Figure 16. Depth hydrographs for CRC border #3, 8/15/79. Volume balance after 1 hour, k = 1.770 in/hr^a, a = 0.449. (Slope = 0.0001)


450.0
DEPTH (FT)
0.5
0.0
TIME (MIN)
50
100
150
200
250
300
350
400
450


250.0
DEPTH (FT)
TIME (MIN)
50
100
150
200
250
300
350
400
450


610.0
DEPTH (FT)
0.5
0.0
50
100
200
250
300
350
400
450

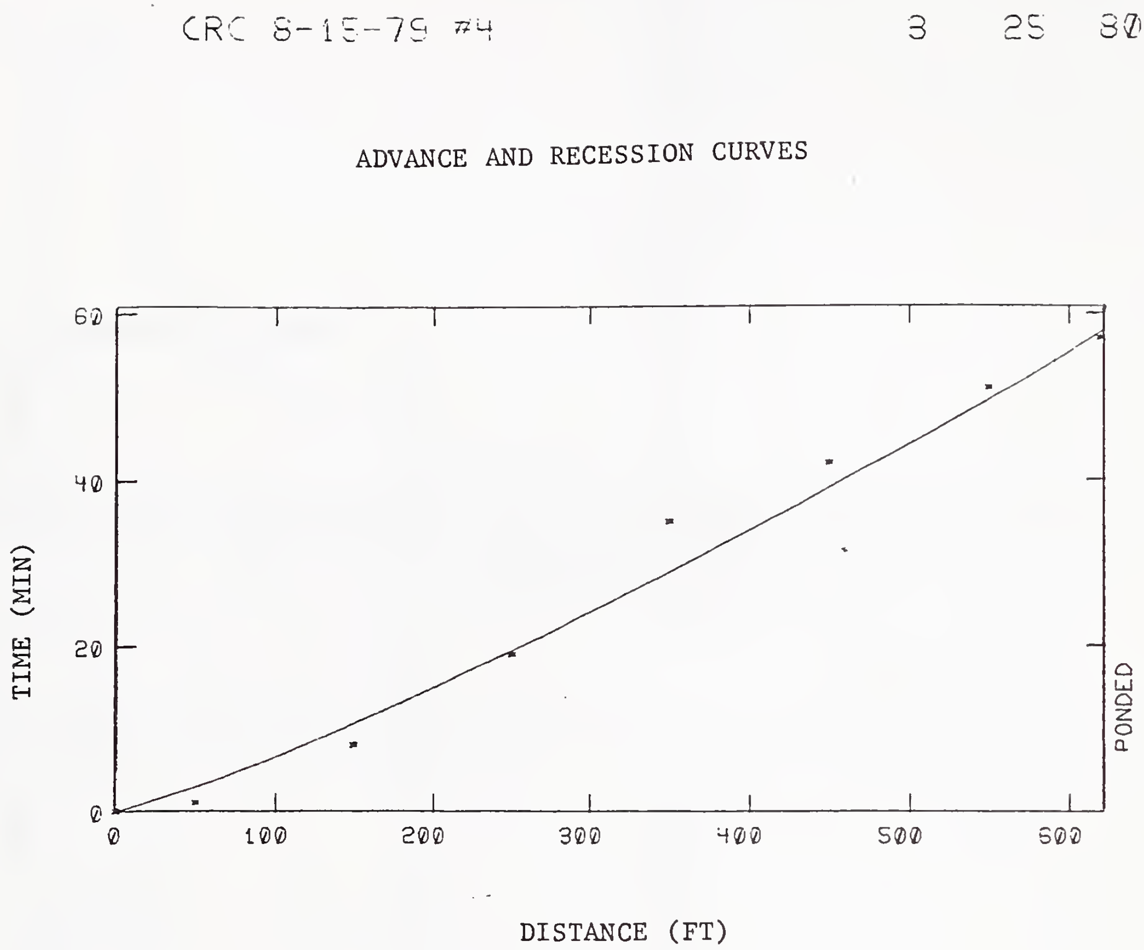
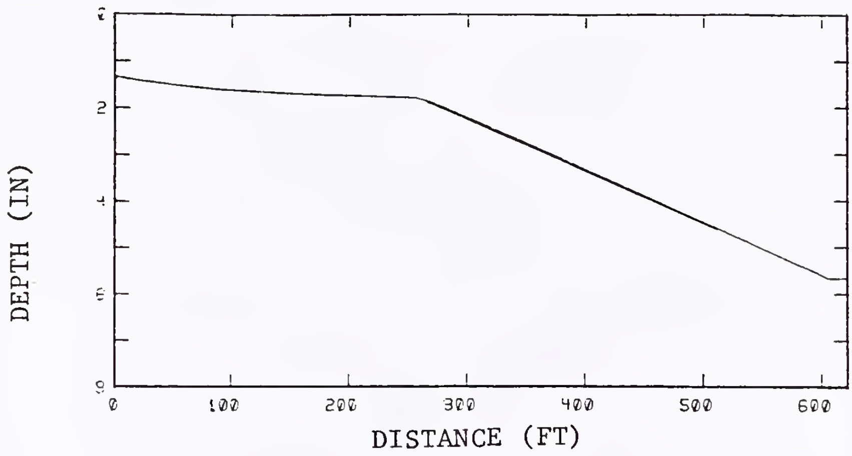


Figure 17. Advance and recession curves for CRC border #4, 8/15/79. Infiltration constants k = 1.105 in/hr^{a}, a = 0.644.

SUBSURFACE PROFILE



FLOW RATE 0.0678 CFS/FT INFILTRATION CONSTANT 1.105 IN/HR**A

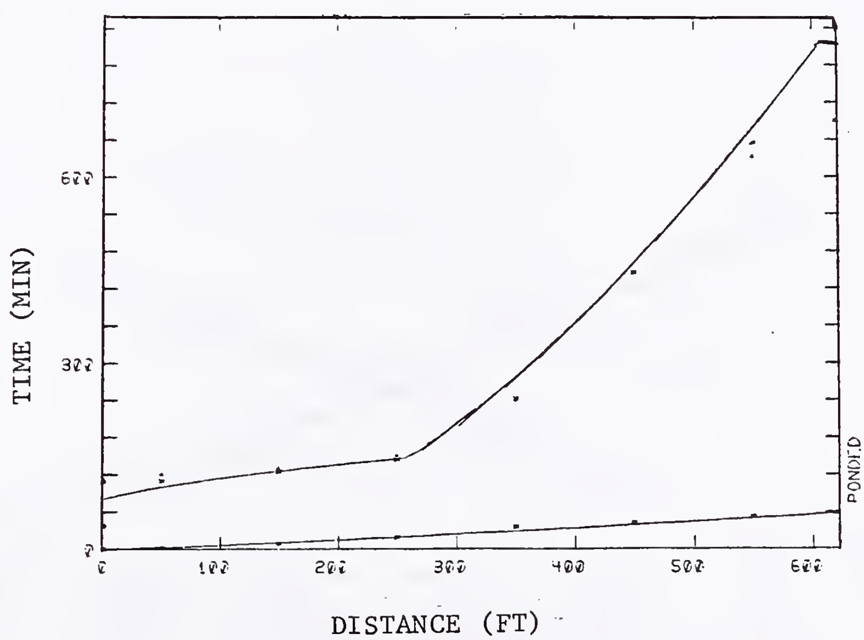
BOTTOM SLOPE 0.100 % INFILTRATION POWER 0.644

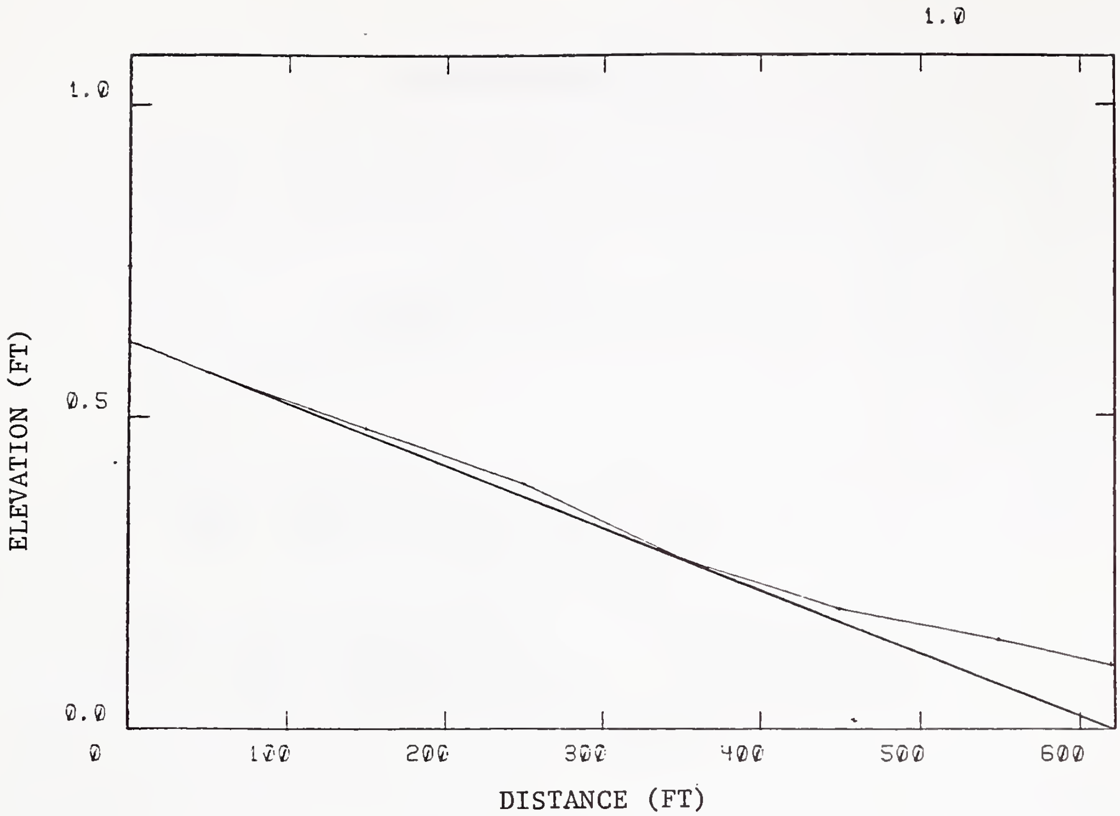
MANNING N 0.147 FINAL INFILTRATION RATE 0.000 IN/HR

APPLICATION TIME 37.0 MIN.

CRC 8-15-79 #4 8 25 80

ADVANCE AND RECESSION CURVES





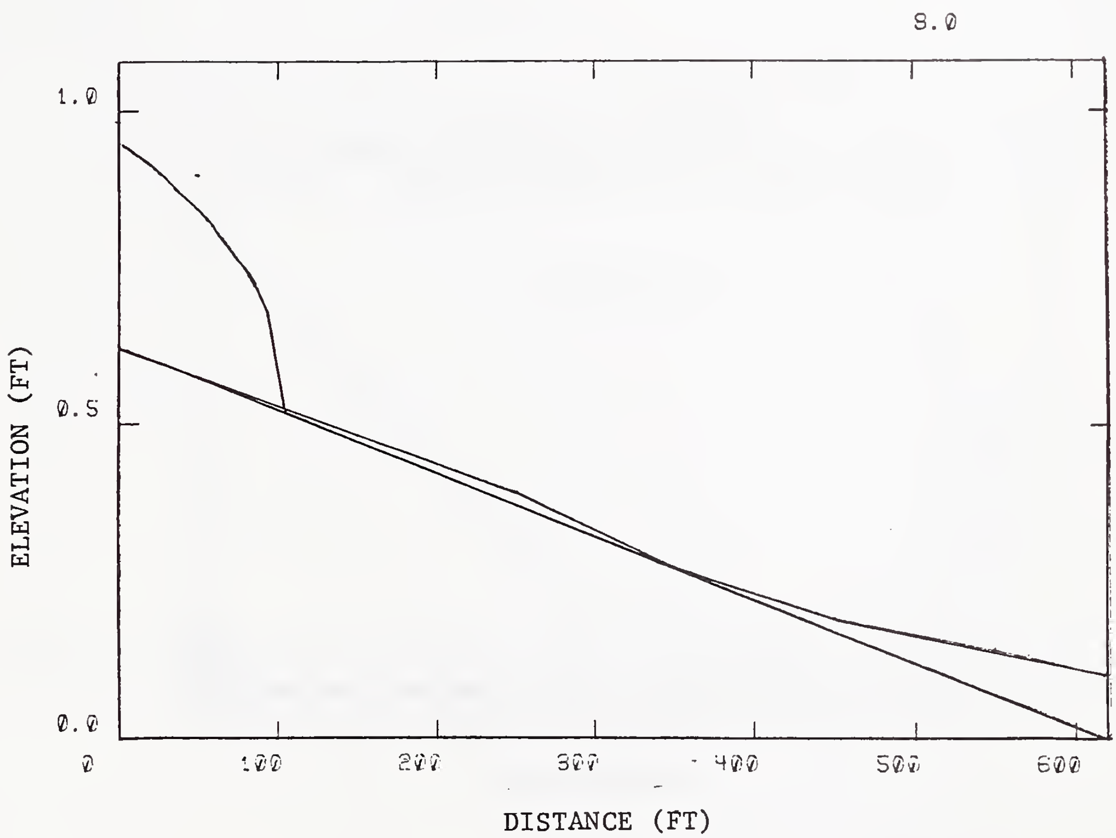
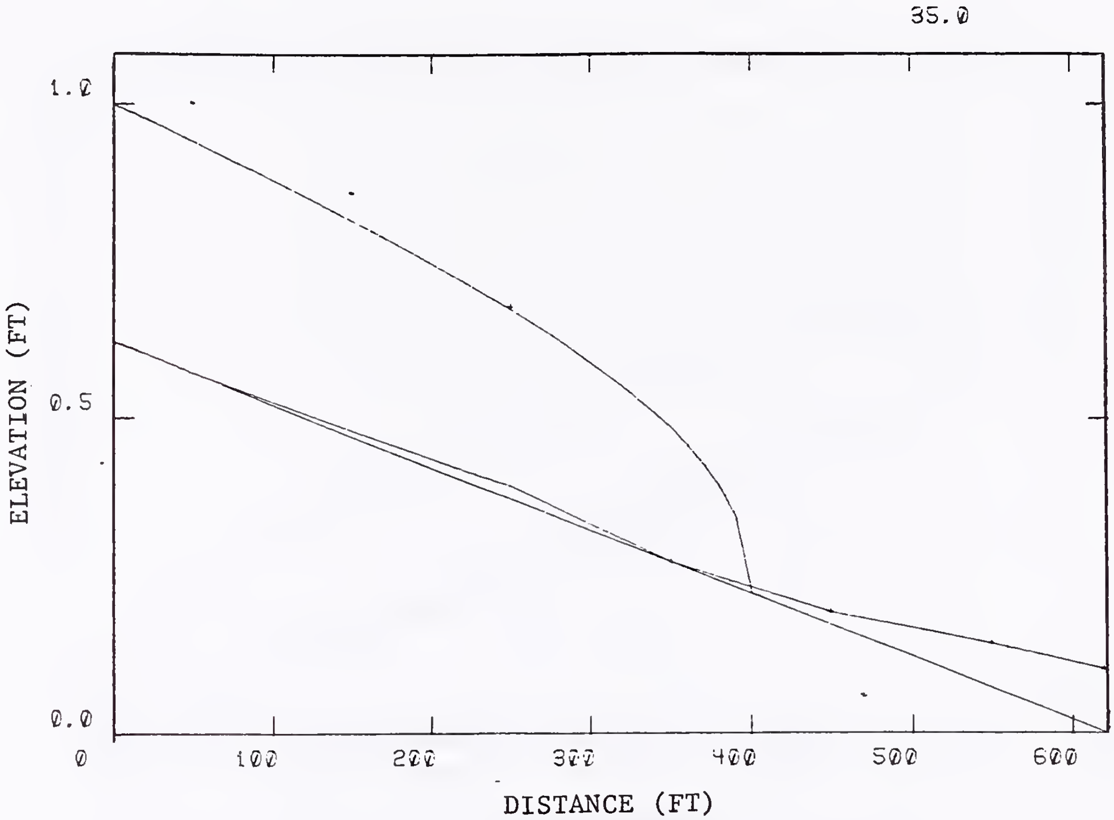
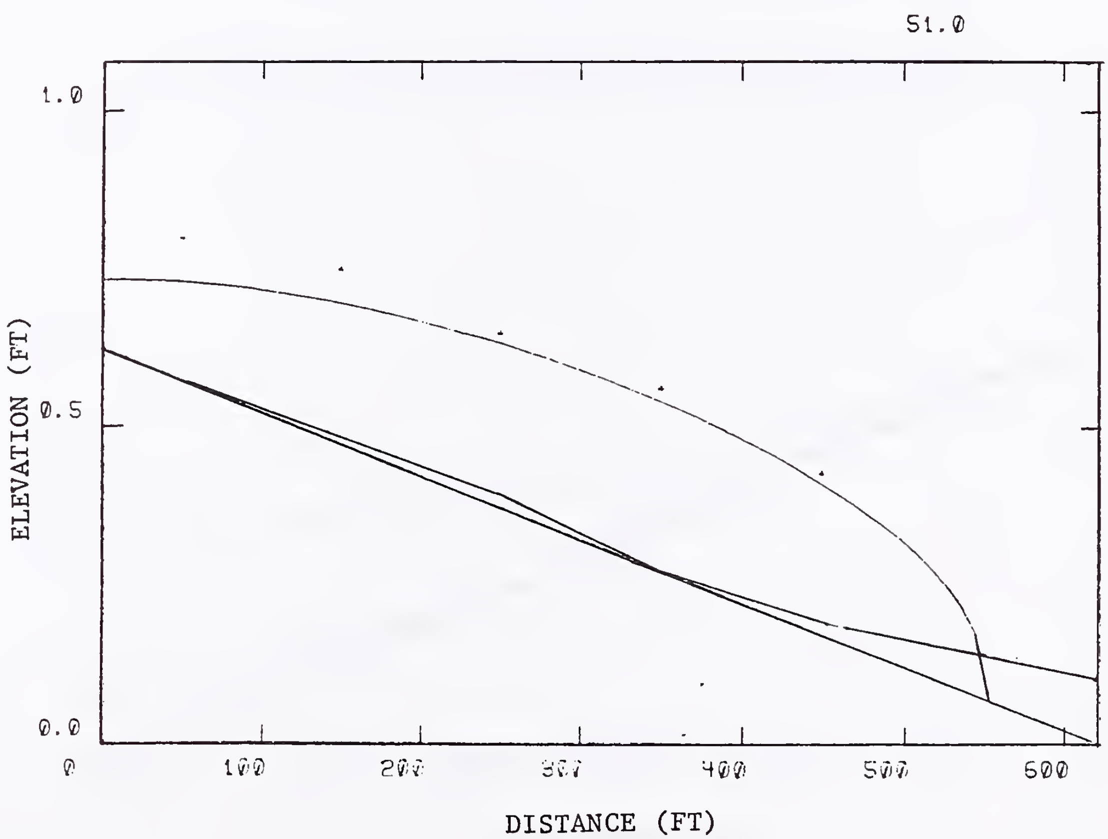
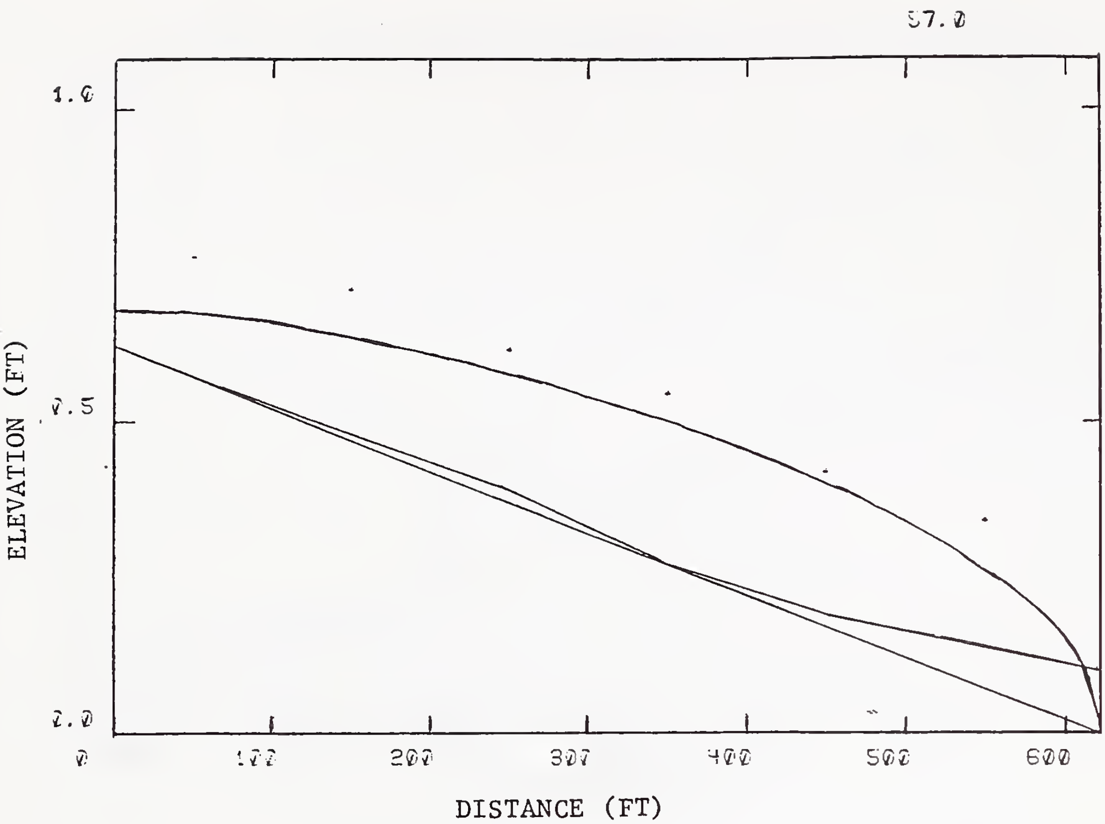
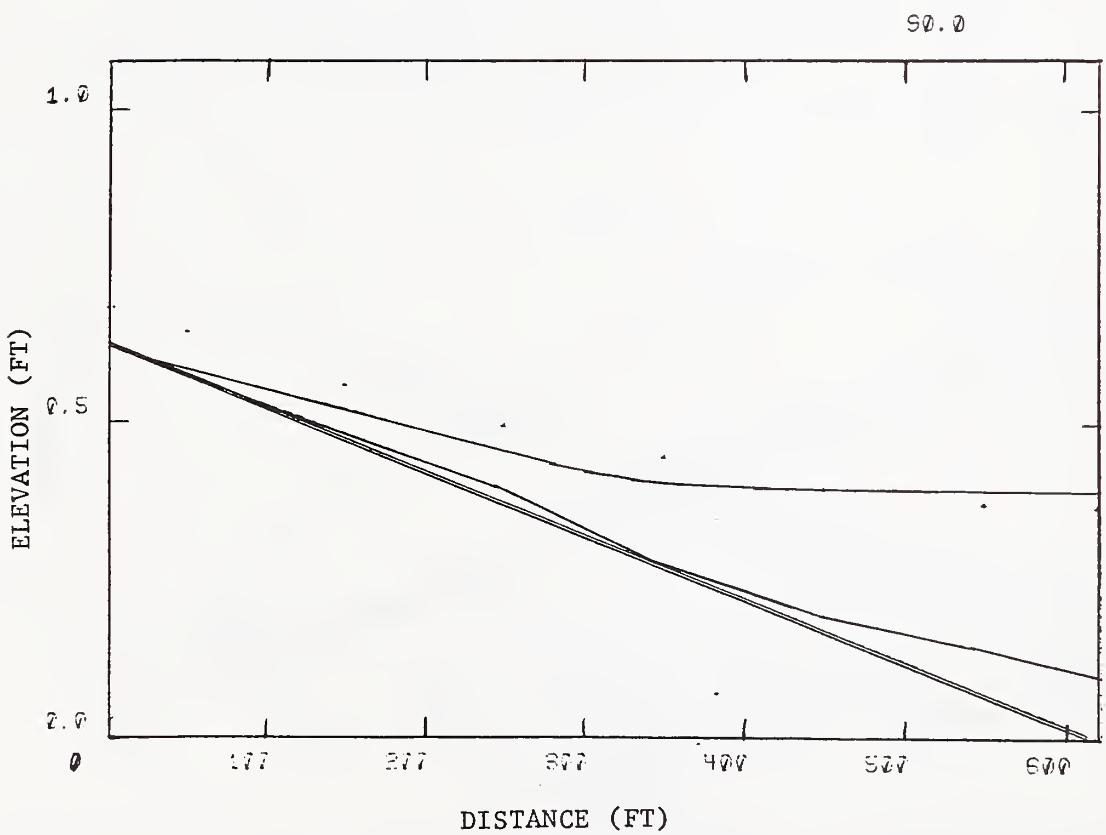


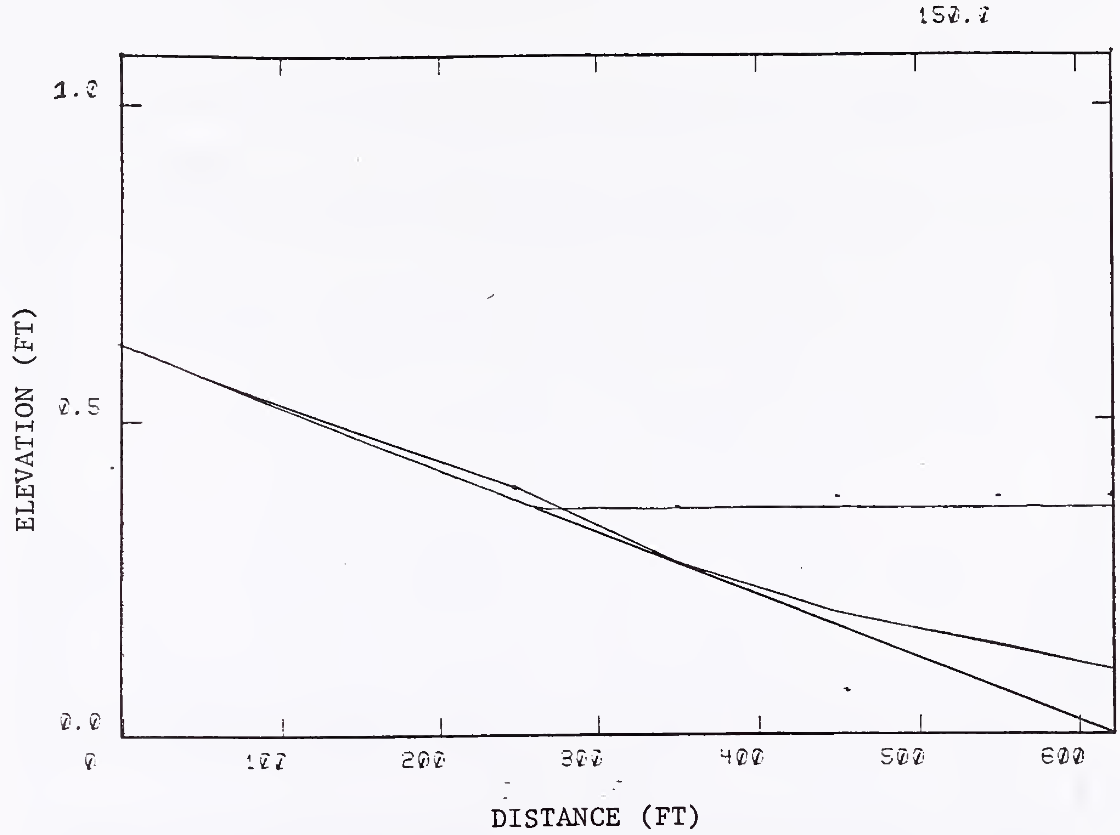
Figure 18. Profiles for CRC border #4, 8/15/79. Infiltration constants $k = 1.105$ in/hr^a, $a = 0.644$.

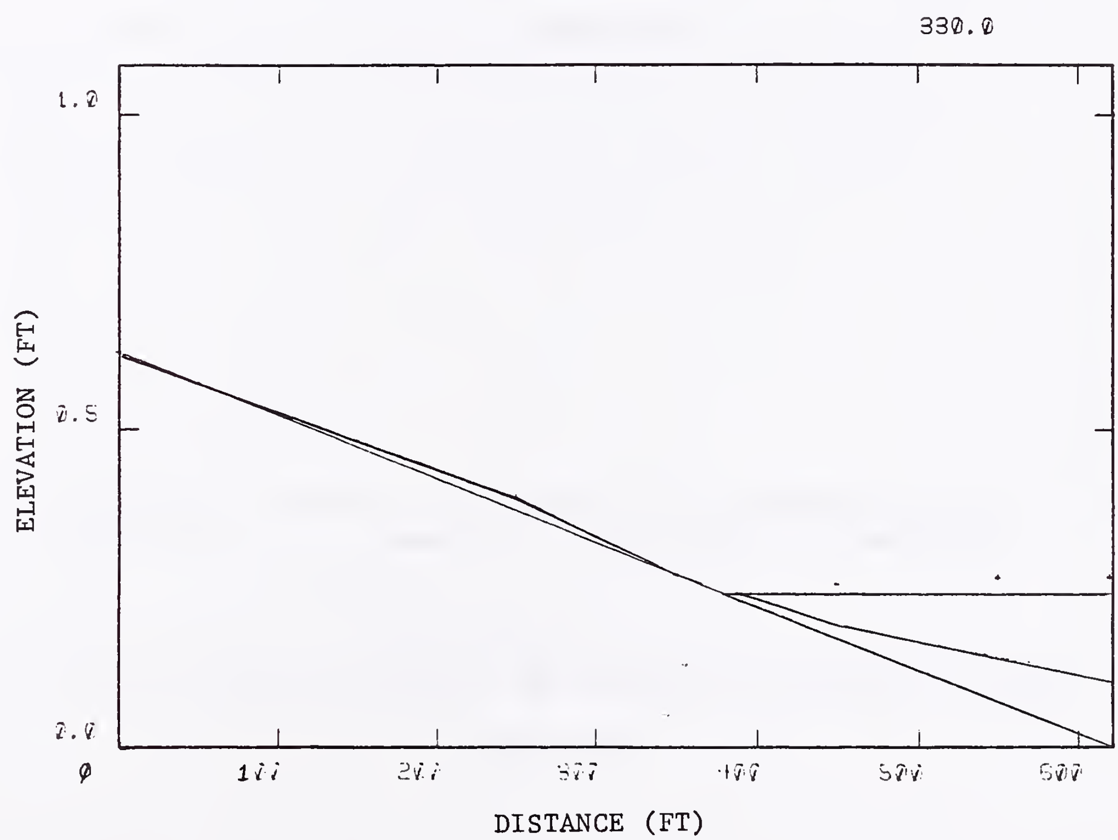

35.0
1.0
0.5
0.0
ELEVATION (FT)
0
100
200
300
400
500
600
DISTANCE (FT)


51.0
1.0
0.5
0.0
ELEVATION (FT)
0
100
200
300
400
500
600
DISTANCE (FT)


57.0
1.0
0.5
0.0
ELEVATION (FT)
0
100
200
300
400
500
600
DISTANCE (FT)


50.0
1.0
0.5
0.0
ELEVATION (FT)
0
100
200
300
400
500
600
DISTANCE (FT)


150.0
1.0
0.5
0.0
0
100
200
300
400
500
600
ELEVATION (FT)
DISTANCE (FT)


330.0
1.0
0.5
0.0
0
100
200
300
400
500
600
ELEVATION (FT)
DISTANCE (FT)

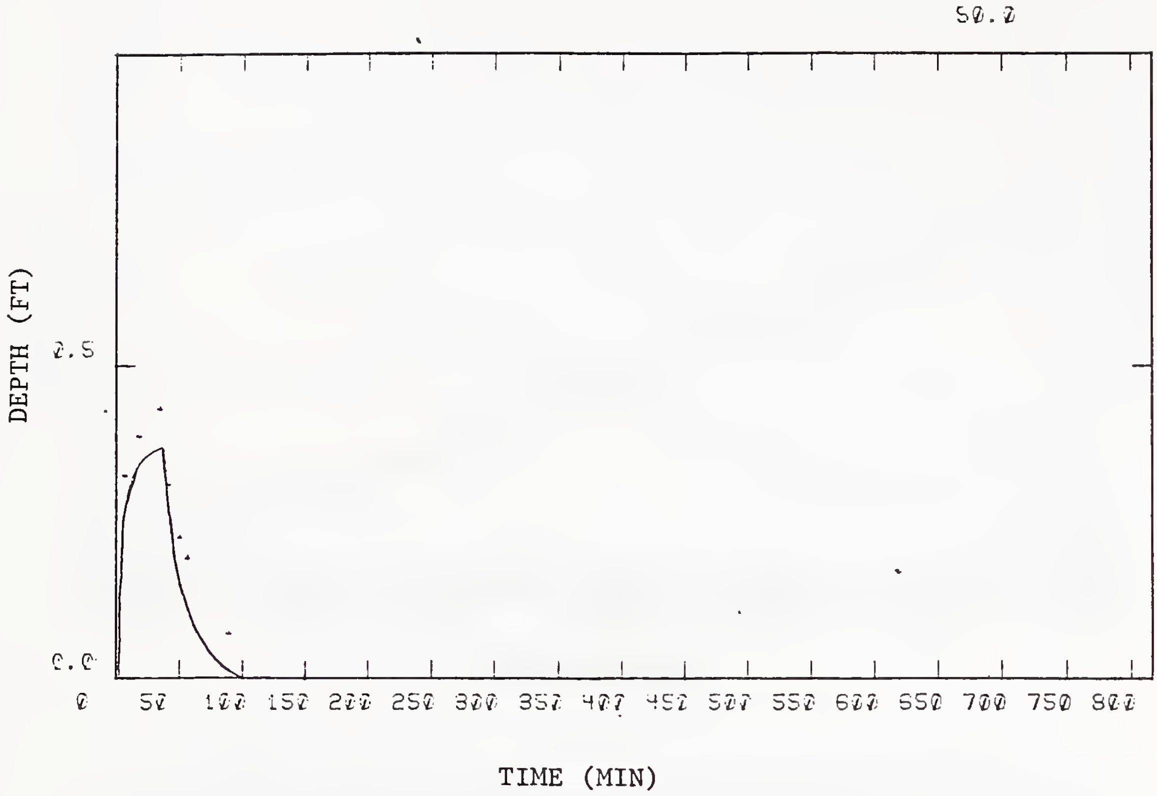
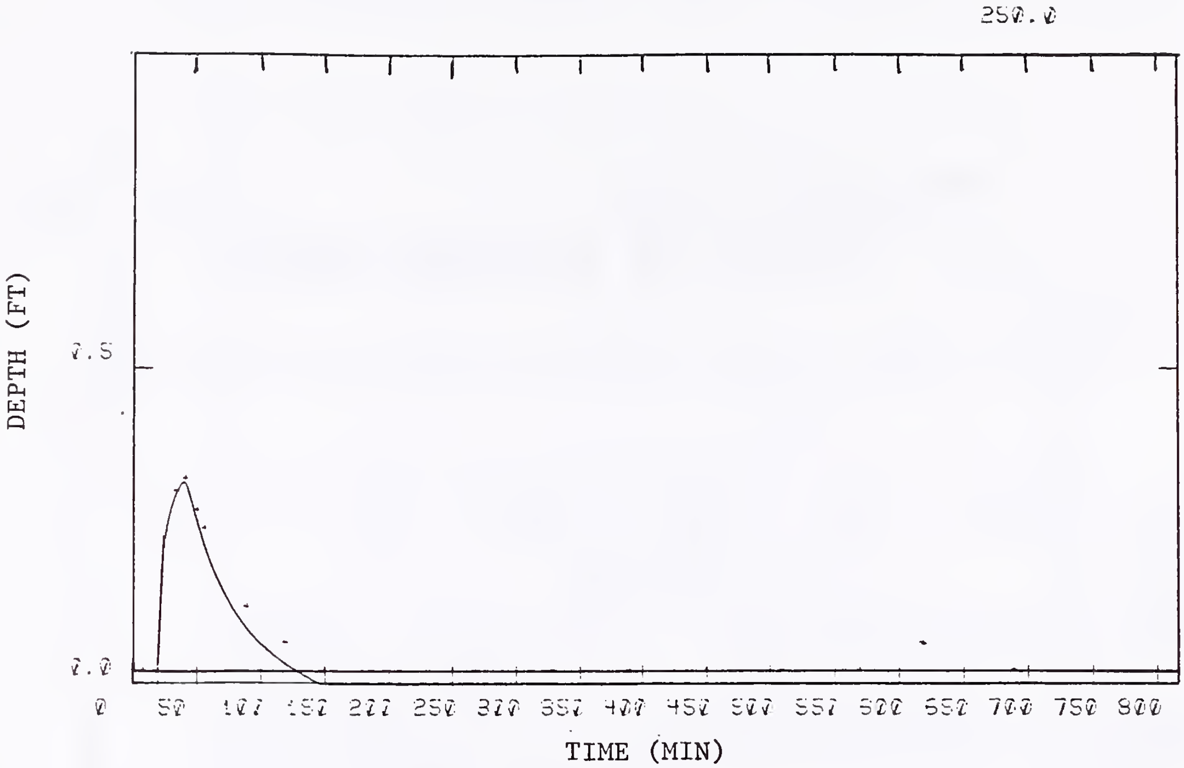
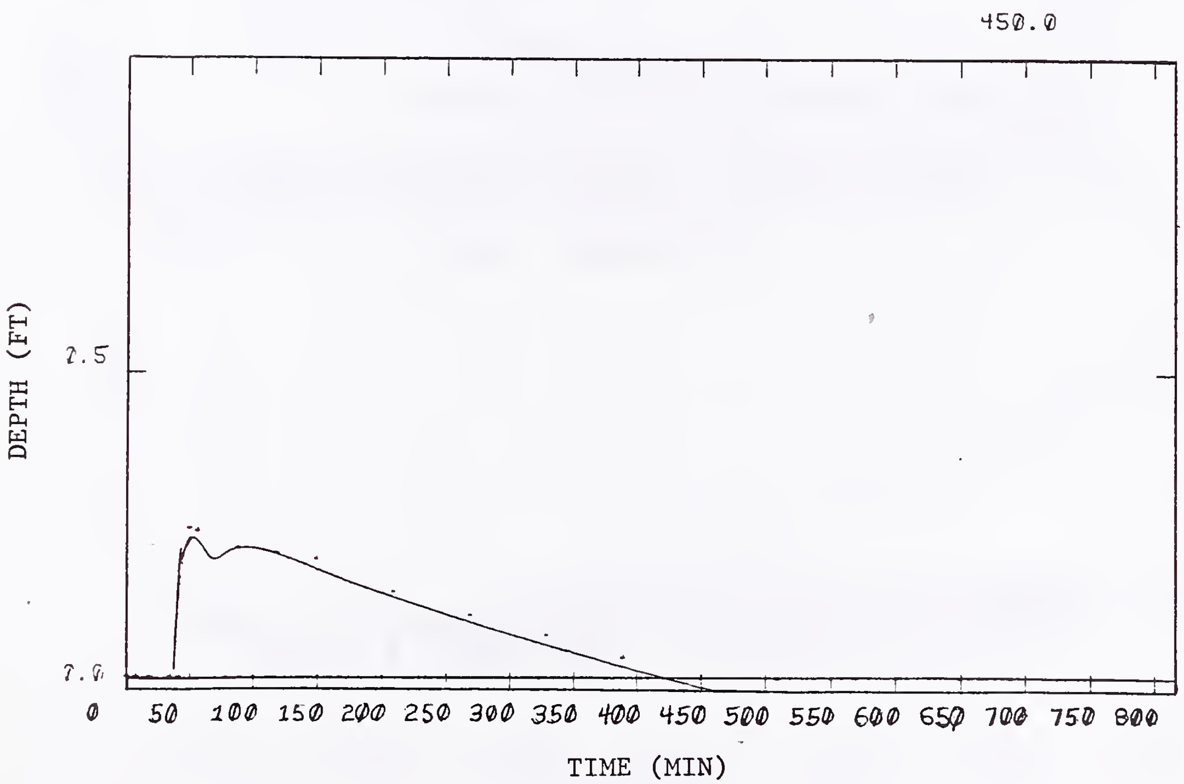


Figure 19. Depth hydrographs for CRC border #4, 8/15/79. Infiltration constants $k = 1.105$ in/hr^a, $a = 0.644$.


250.0
DEPTH (FT)
0.5
0.0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
TIME (MIN)


450.0
DEPTH (FT)
0.5
0.0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
TIME (MIN)

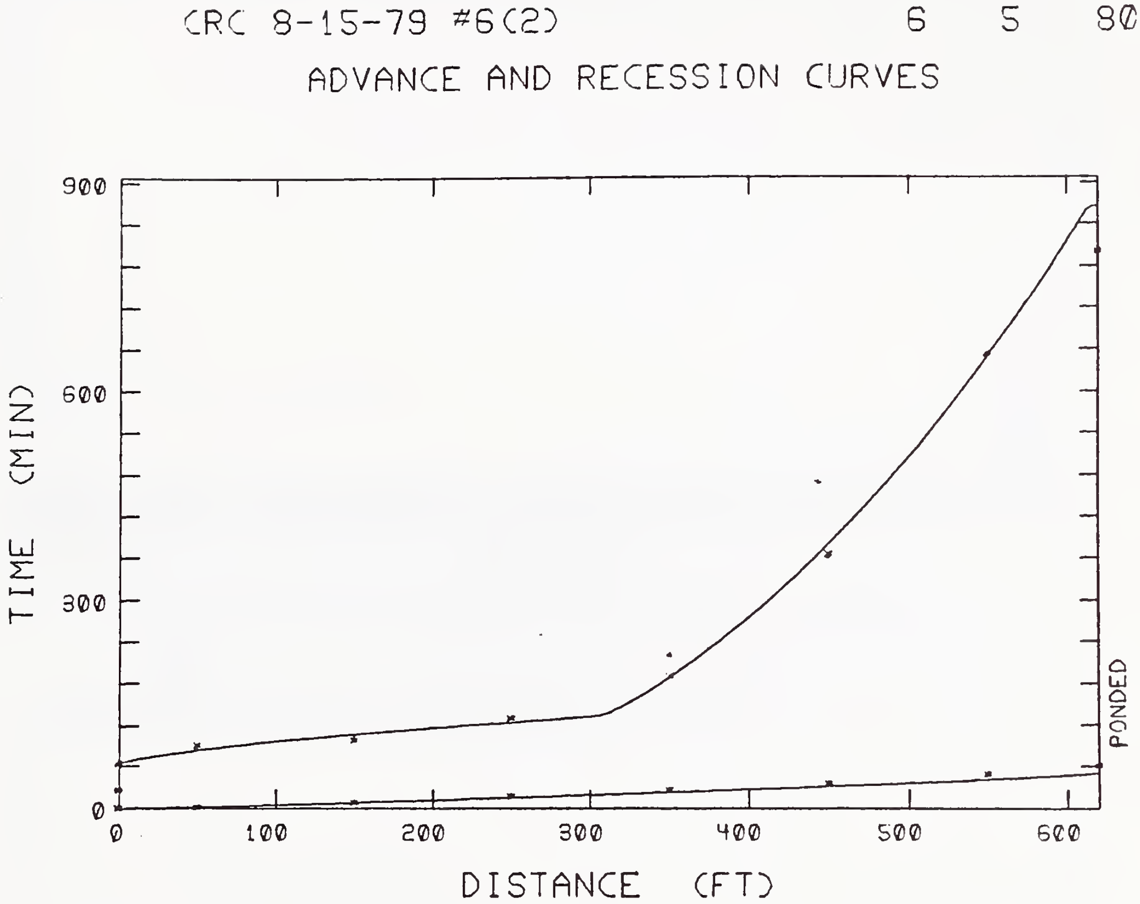
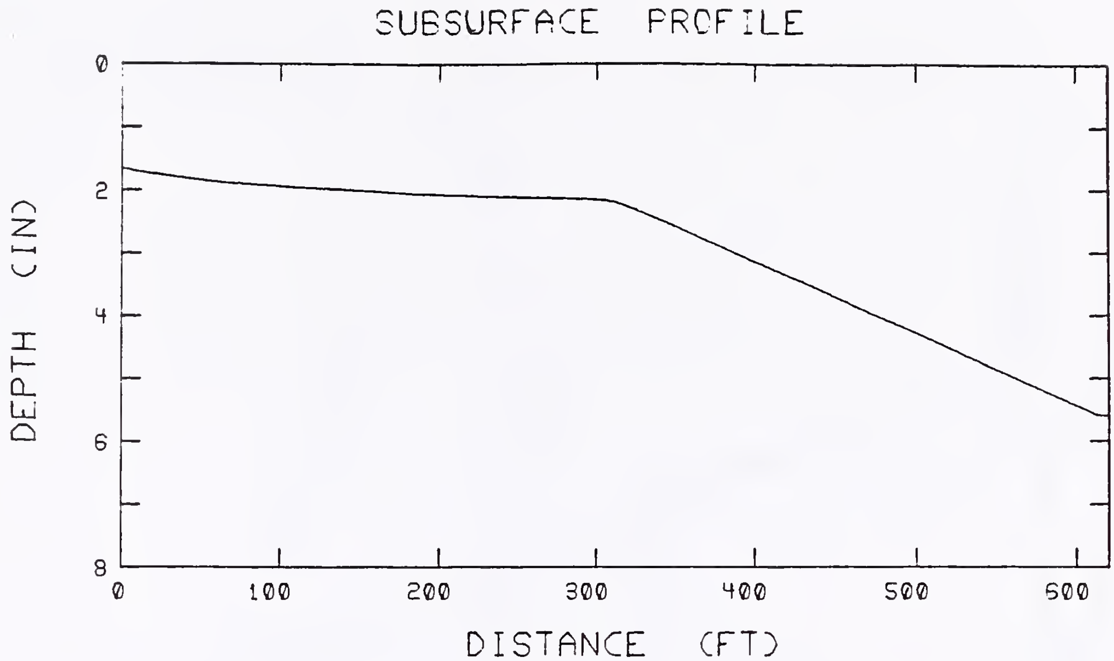


Figure 20. Advance and recession curves for CRC border #6, 8/15/79. Infiltration constants k = 1.590 in/hr^a, a = 0.483.



FLOW RATE 0.1016 CFS/FT

BOTTOM SLOPE 0.100 %

MANNING N 0.133

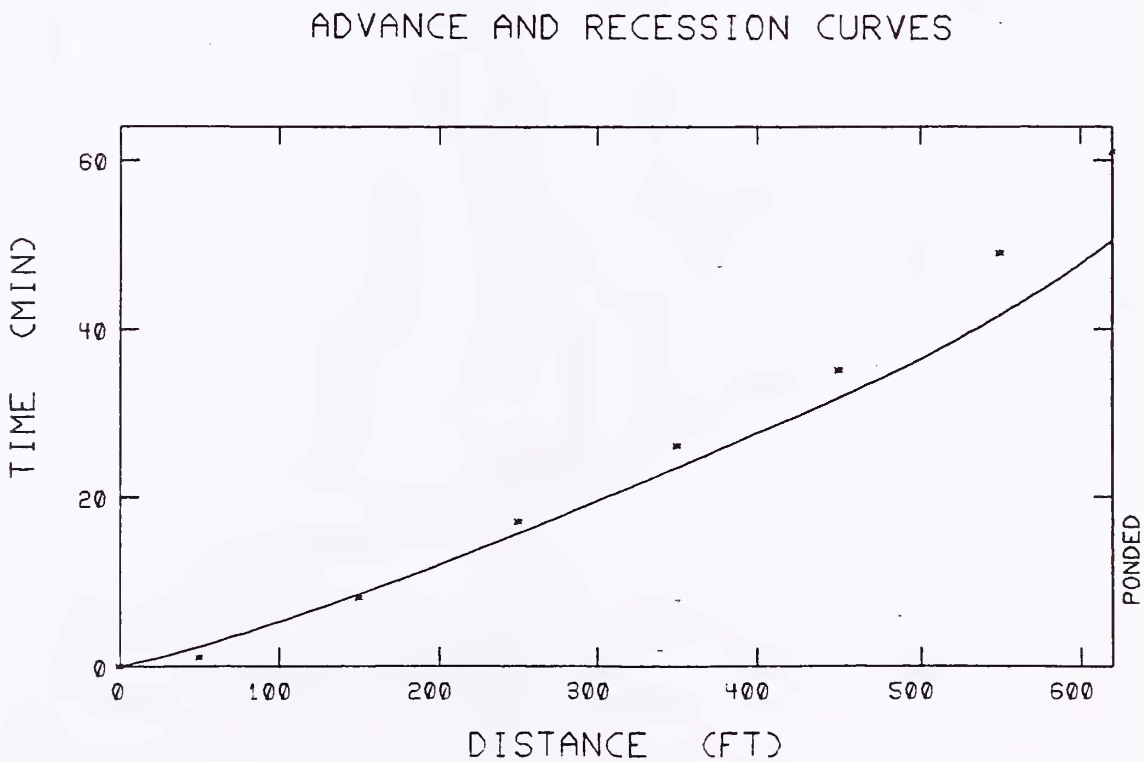
APPLICATION TIME 25.0 MIN.

INFILTRATION CONSTANT 1.590 IN/HR**A

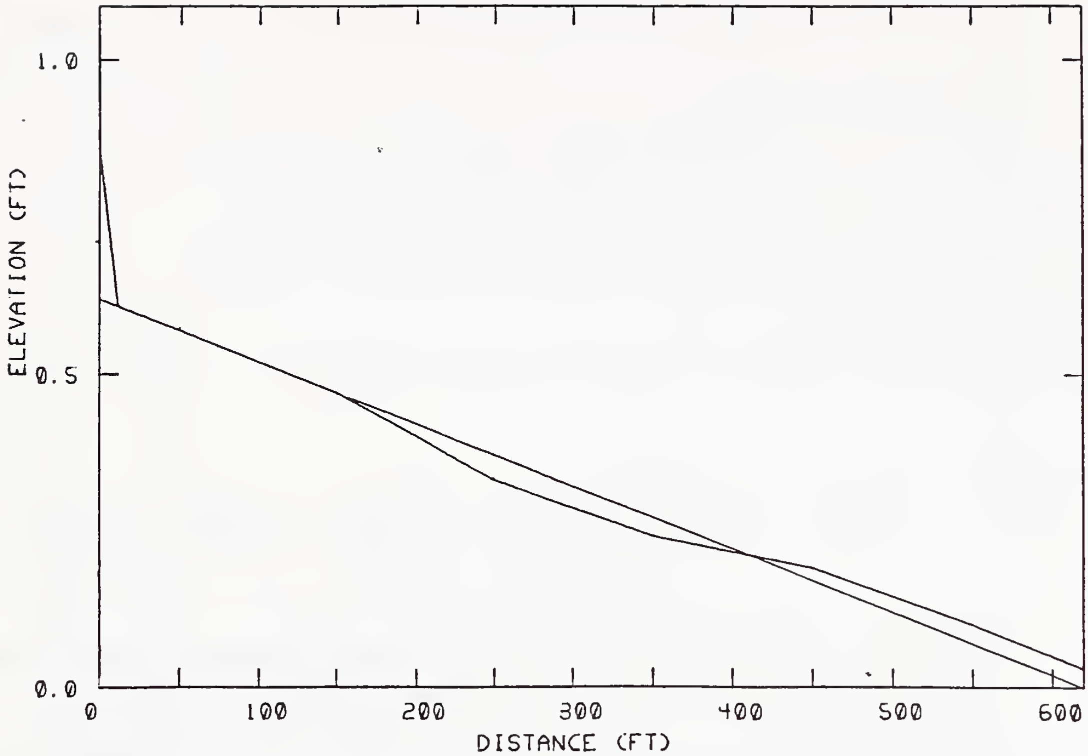
INFILTRATION POWER 0.483

FINAL INFILTRATION RATE 0.000 IN/HR

CRC 8-15-79 #6(2) 6 5 80



1.0



17.0

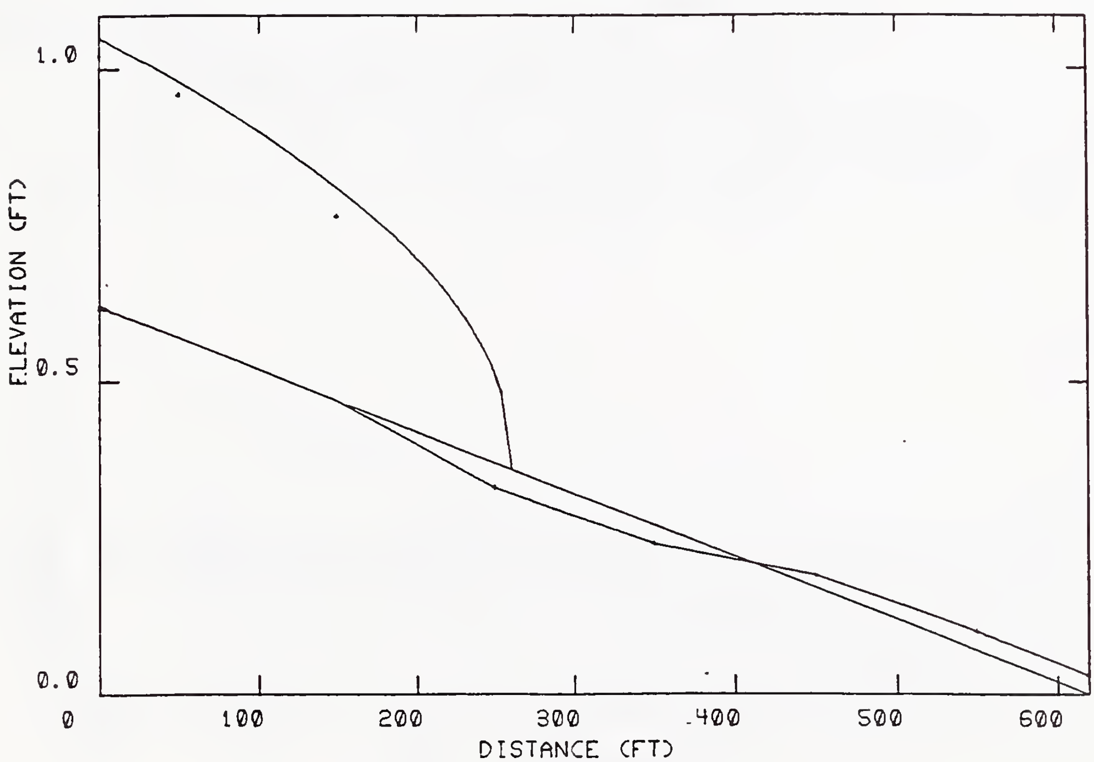
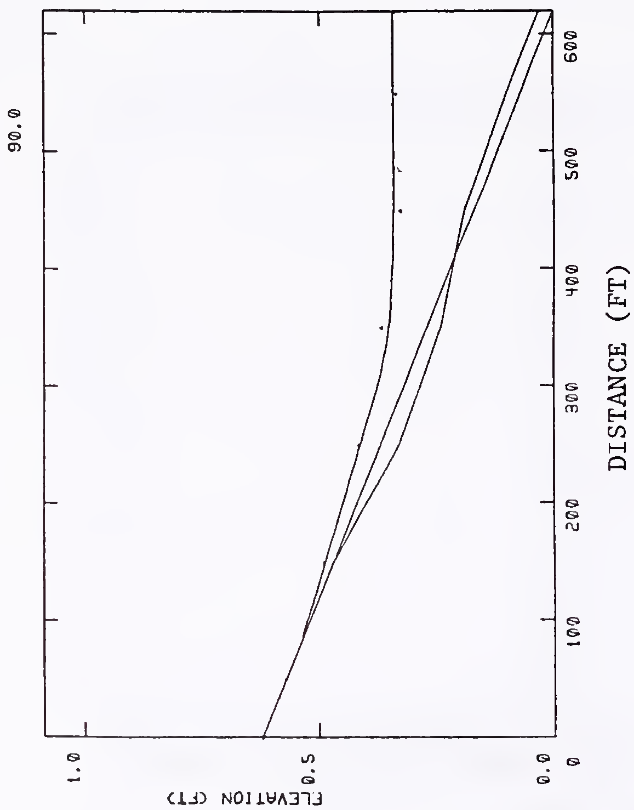
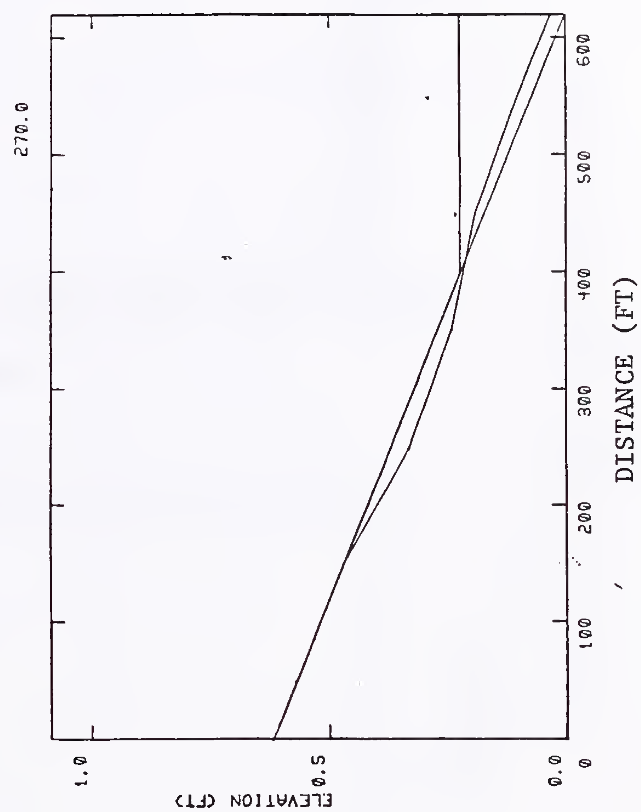
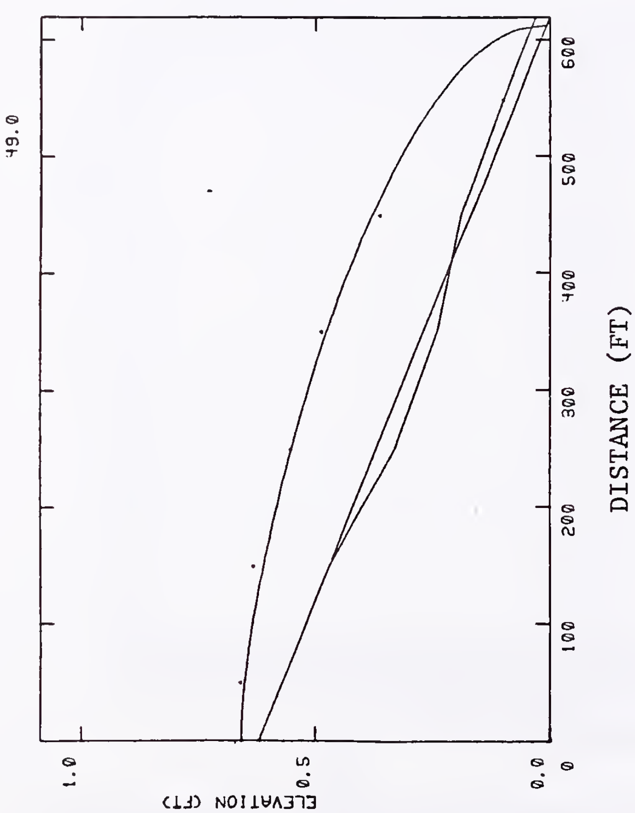
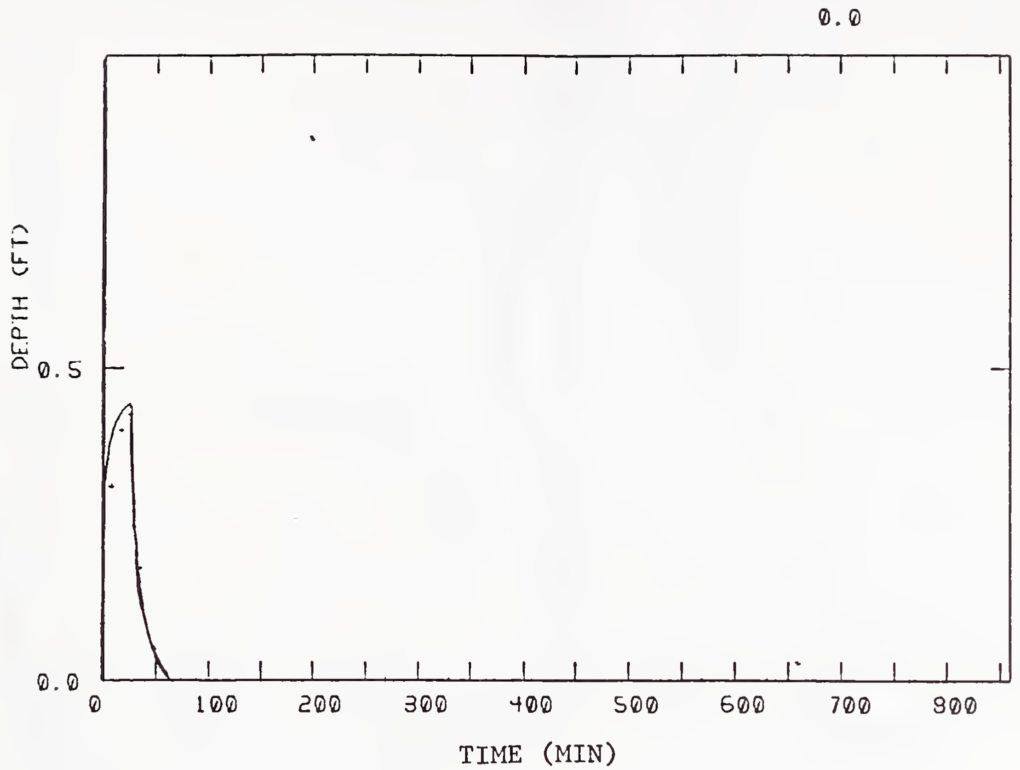


Figure 21. Profiles for CRC border #6, 8/15/79. Infiltration constants k = 1.590 in/hr^a, a = 0.483.


90.0
ELEVATION (FT)
0.0
0.5
1.0
DISTANCE (FT)
0
100
200
300
400
500
600


270.0
ELEVATION (FT)
0.0
0.5
1.0
DISTANCE (FT)
0
100
200
300
400
500
600


49.0
ELEVATION (FT)
0.0
0.5
1.0
DISTANCE (FT)
0
100
200
300
400
500
600



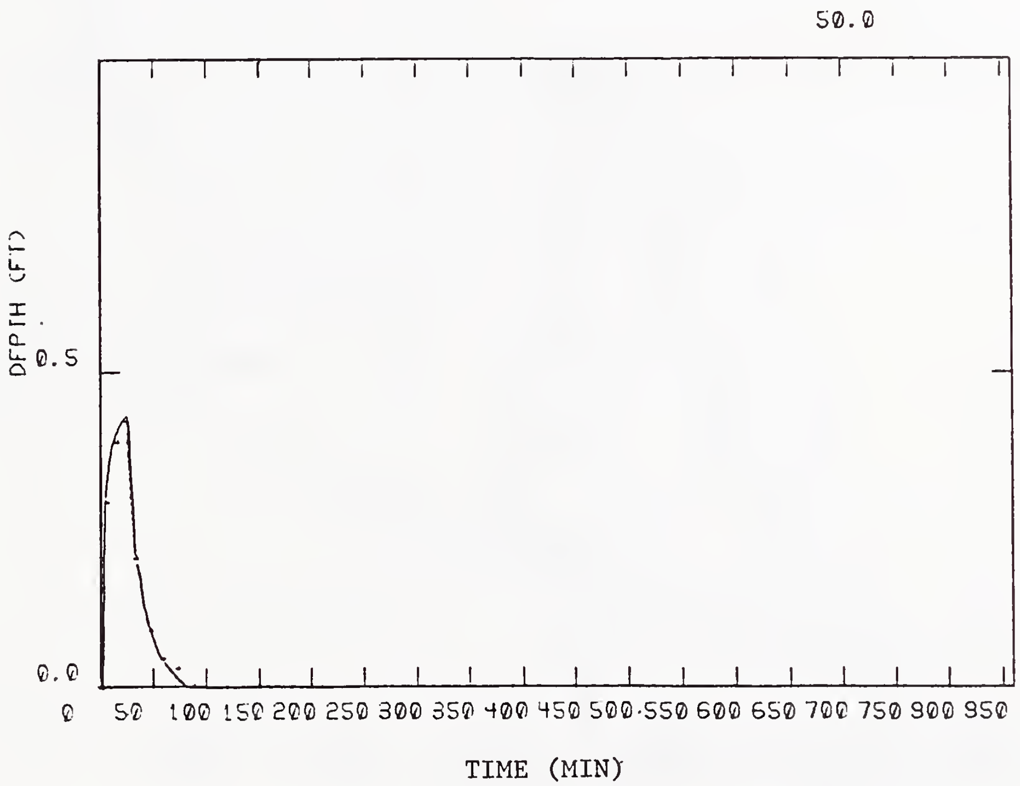
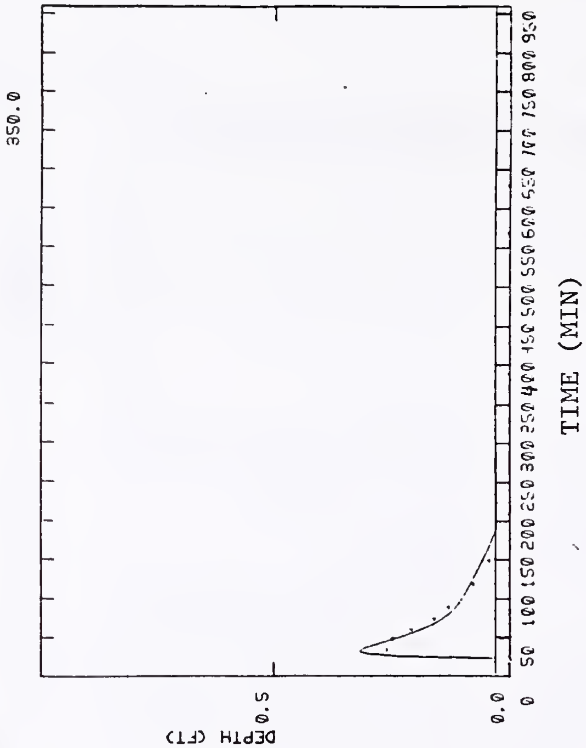
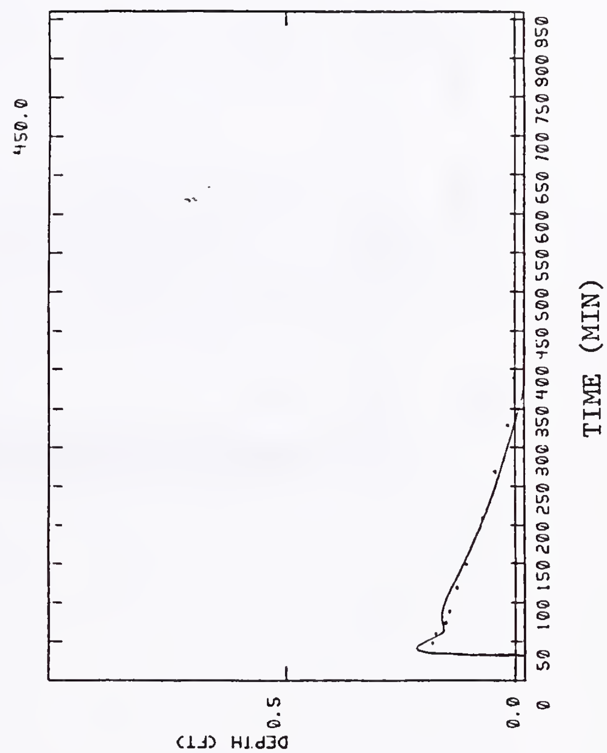
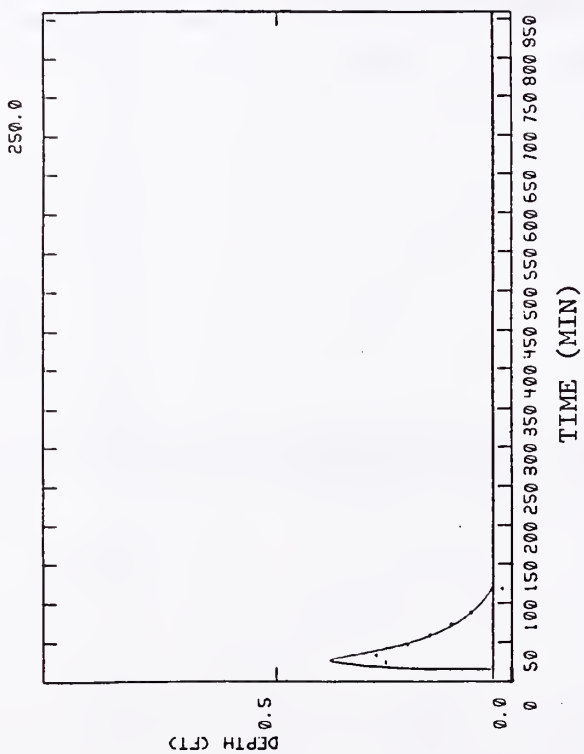


Figure 22. Depth hydrographs for CRC border #6, 8/15/79. Infiltration constants k = 1.590 in/hr^a, a = 0.644.


350.0
DEPTH (FT)
0.5
0.0
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750 800 950
TIME (MIN)


450.0
DEPTH (FT)
0.5
0.0
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750 900 950
TIME (MIN)


250.0
DEPTH (FT)
0.5
0.0
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750 800 950
TIME (MIN)

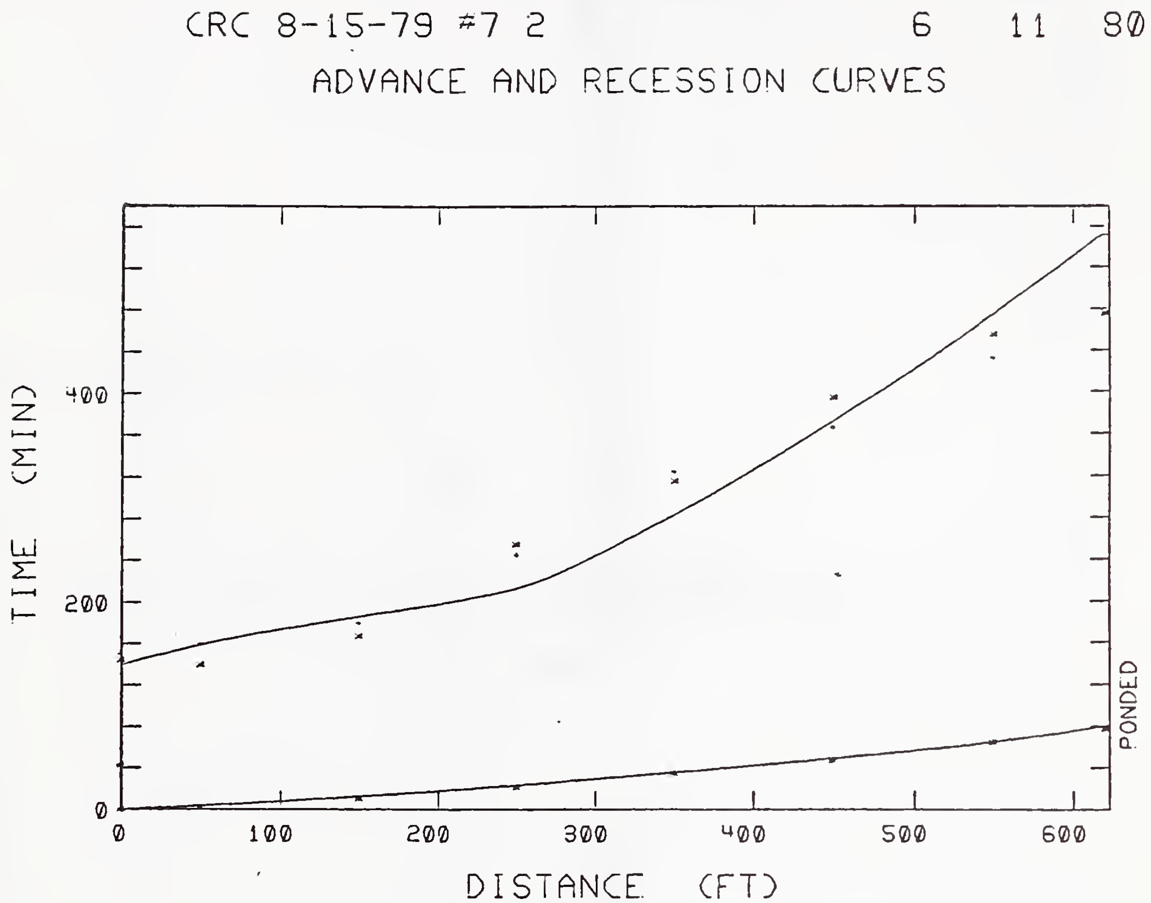
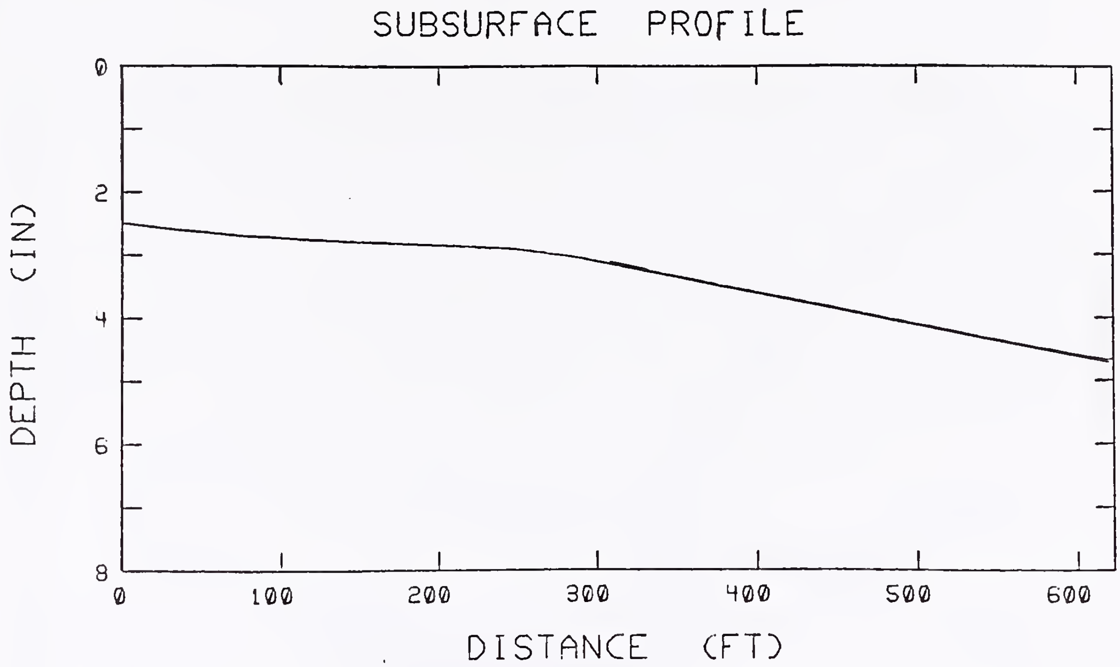


Figure 23. Advance and recession curves for CRC border #7, 8/15/79. Infiltration constants k = 1.614 in/hr^a, a = 0.515.



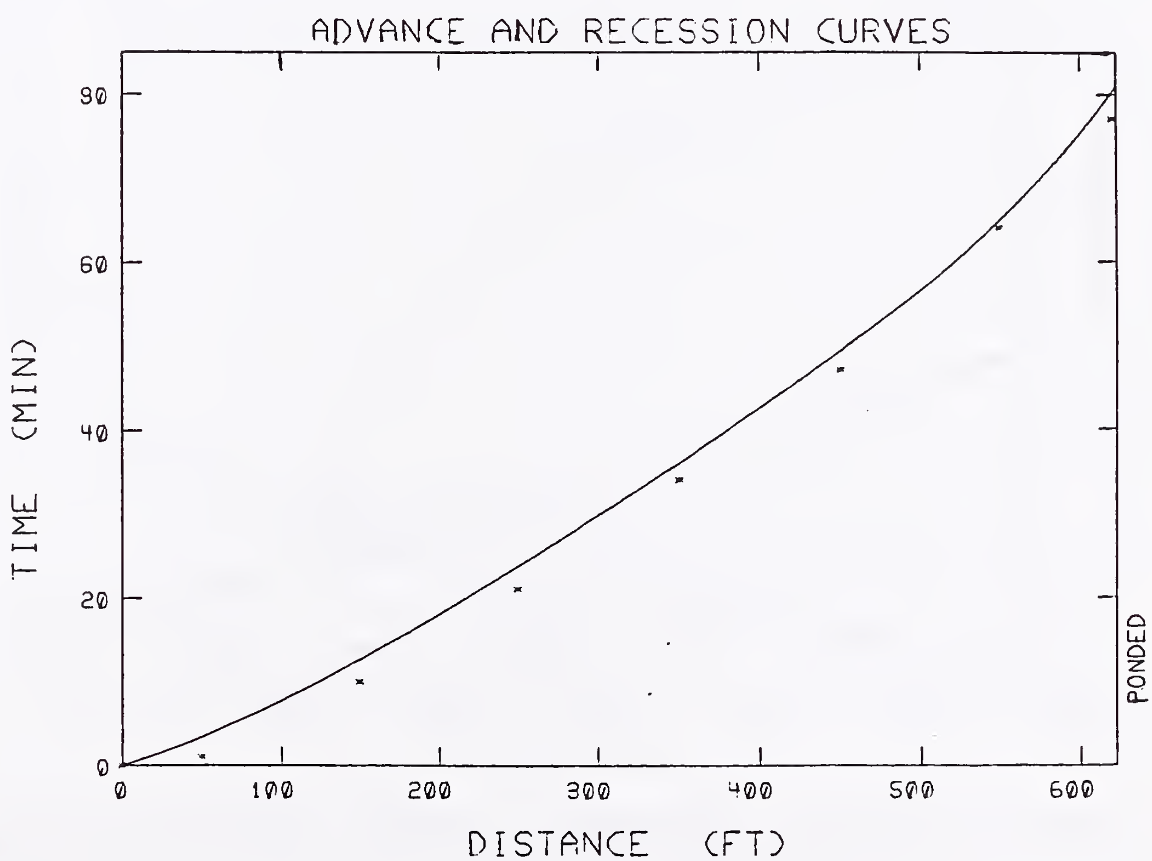
FLOW RATE 0.0677 CFS/FT INFILTRATION CONSTANT 1.614 IN/HR**A

BOTTOM SLOPE 0.050 % INFILTRATION POWER 0.515

MANNING N 0.177 FINAL INFILTRATION RATE 0.000 IN/HR

APPLICATION TIME 43.0 MIN.

CRC 8-15-79 #7 2 6 11 80



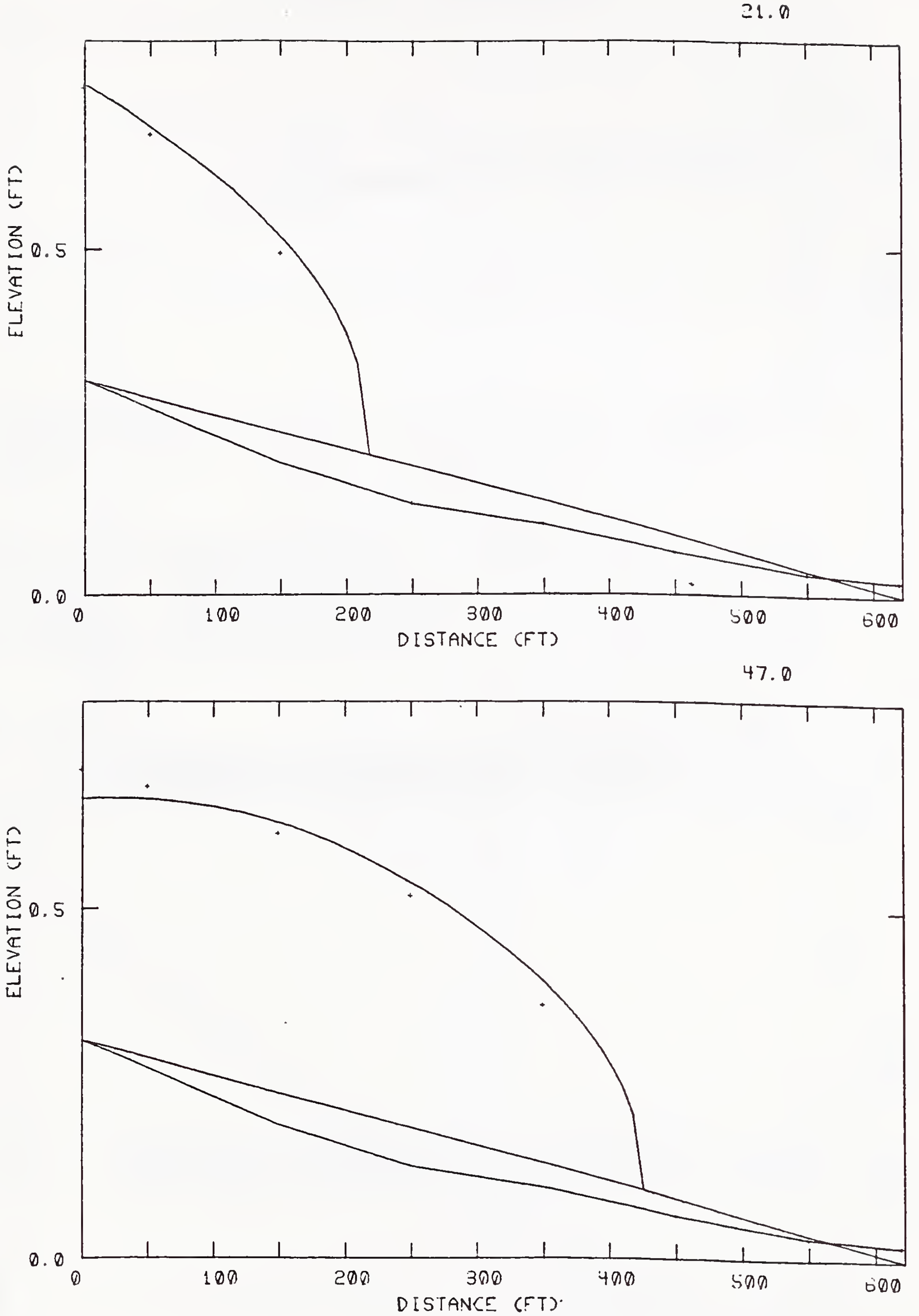
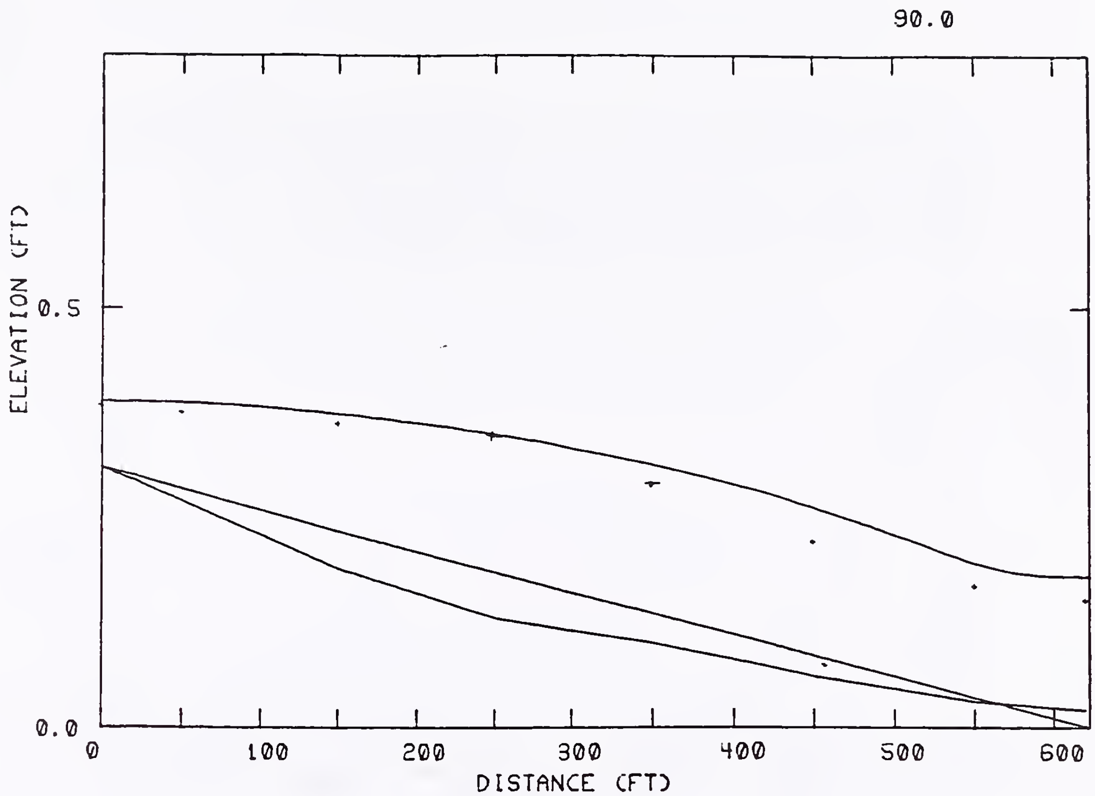
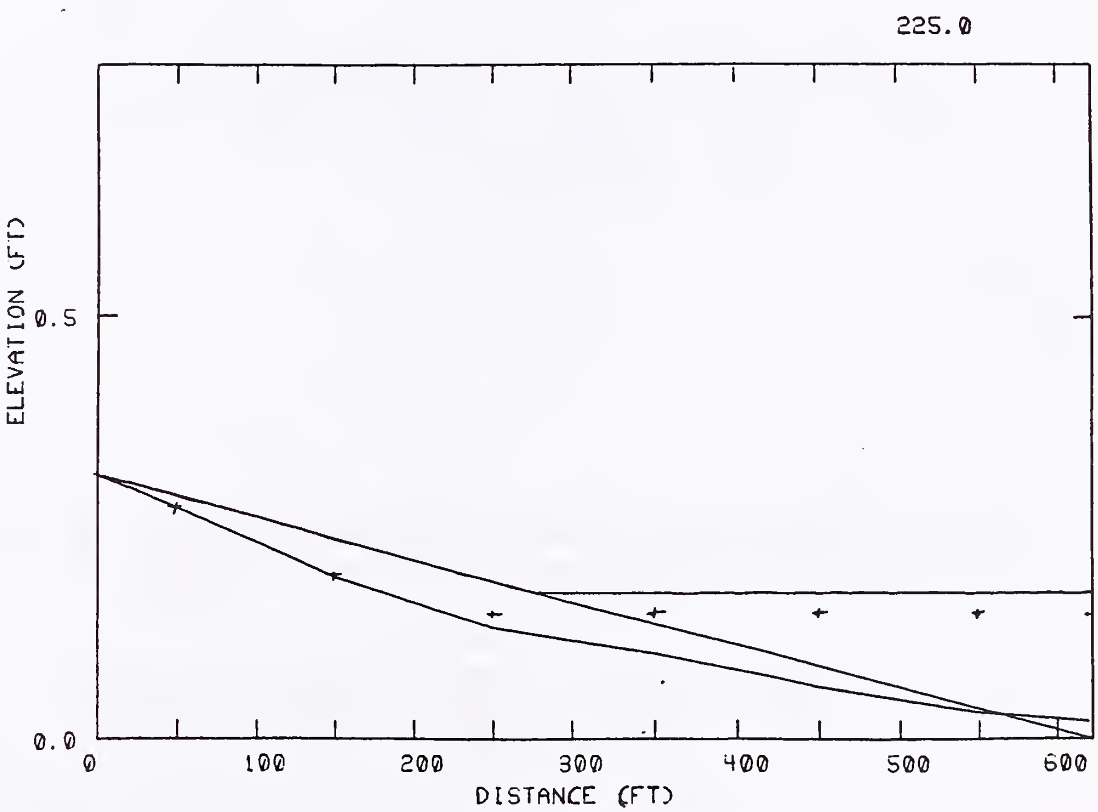


Figure 24. Profiles for CRC border #7, 8/15/79. Infiltration constants $k = 1.614$ in/hr^a, $a = 0.515$.


90.0
ELEVATION (FT)
0.5
0.0
0
100
200
300
400
500
600
DISTANCE (FT)


225.0
ELEVATION (FT)
0.5
0.0
0
100
200
300
400
500
600
DISTANCE (FT)

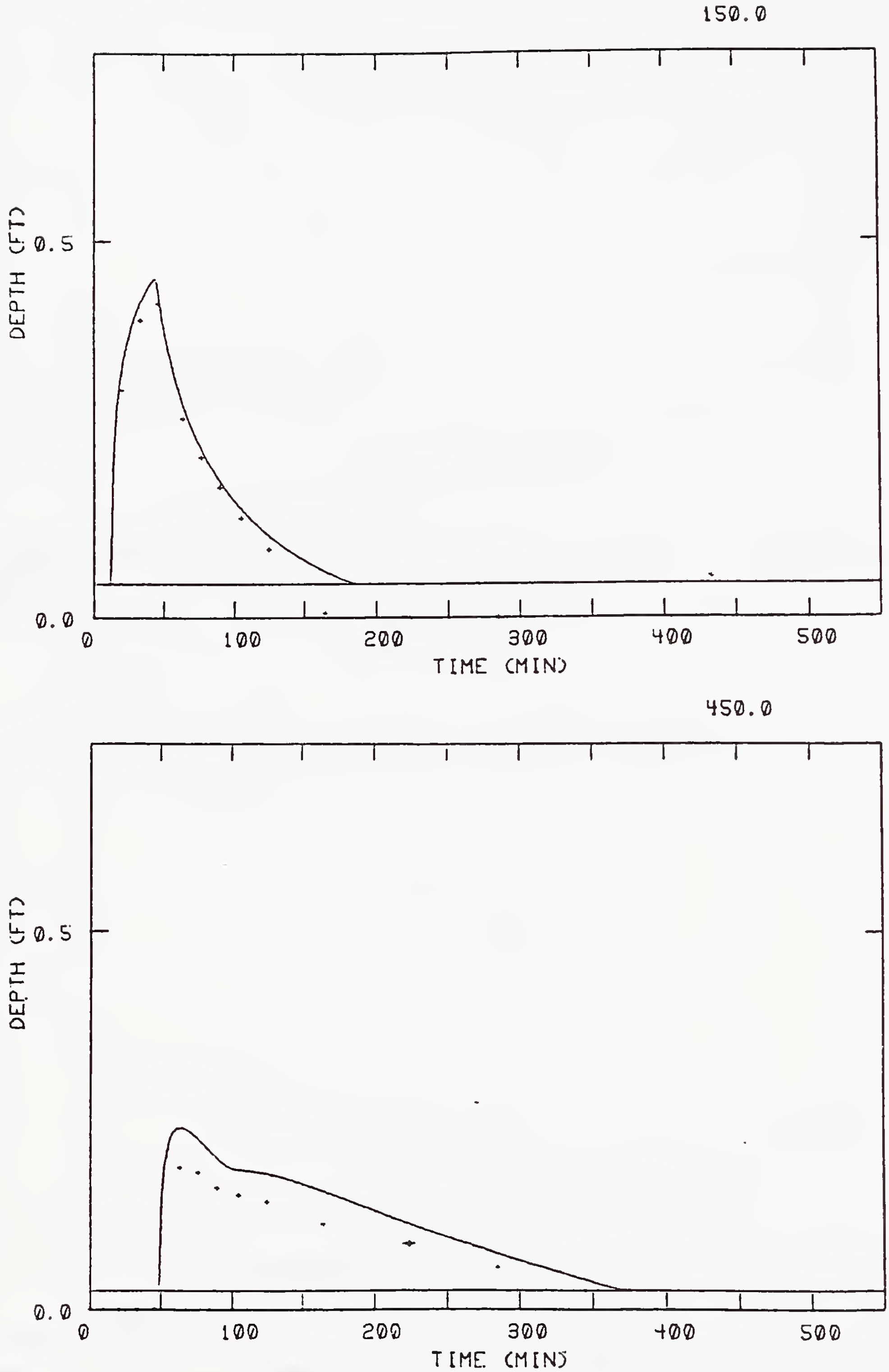


Figure 25. Depth hydrographs for CRC border #7, 8/15/79. Infiltration constants k = 1.614 in/hr^a, a = 0.515.

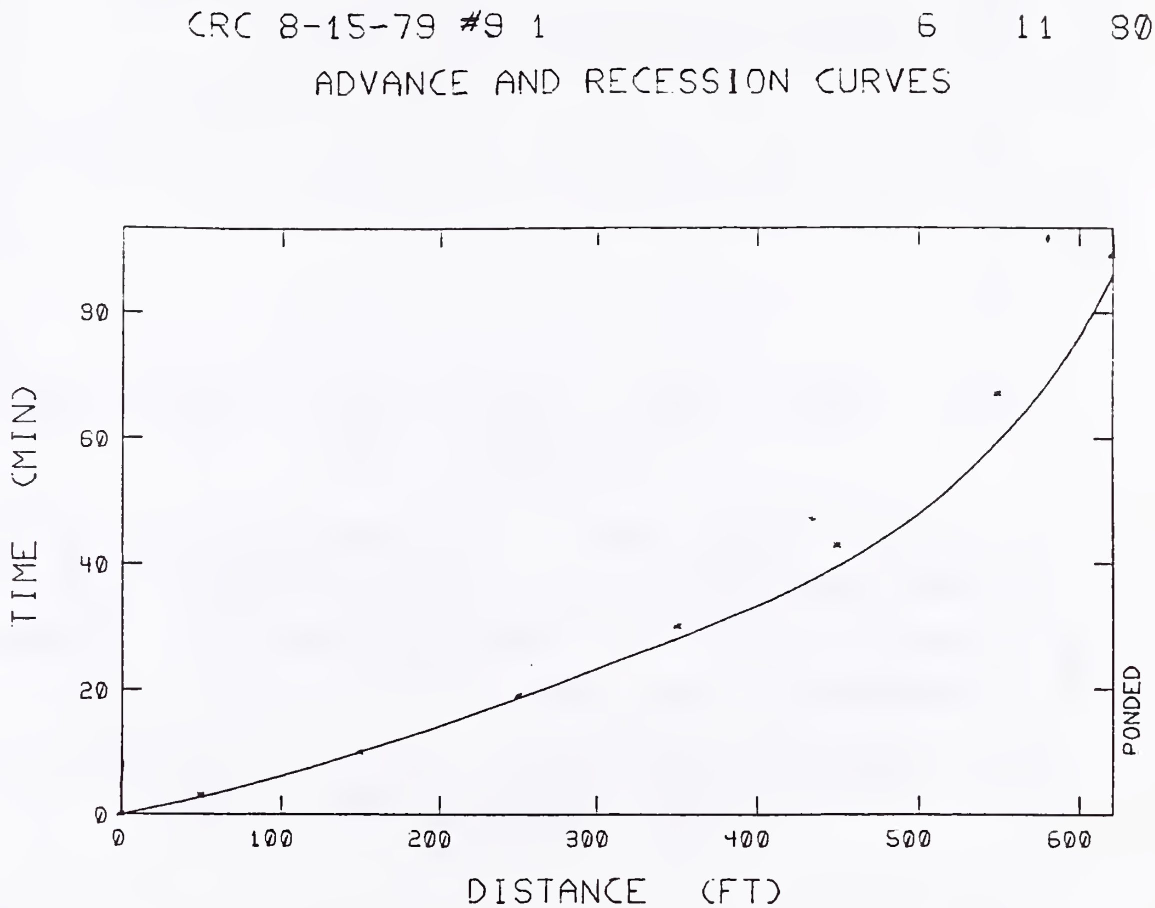
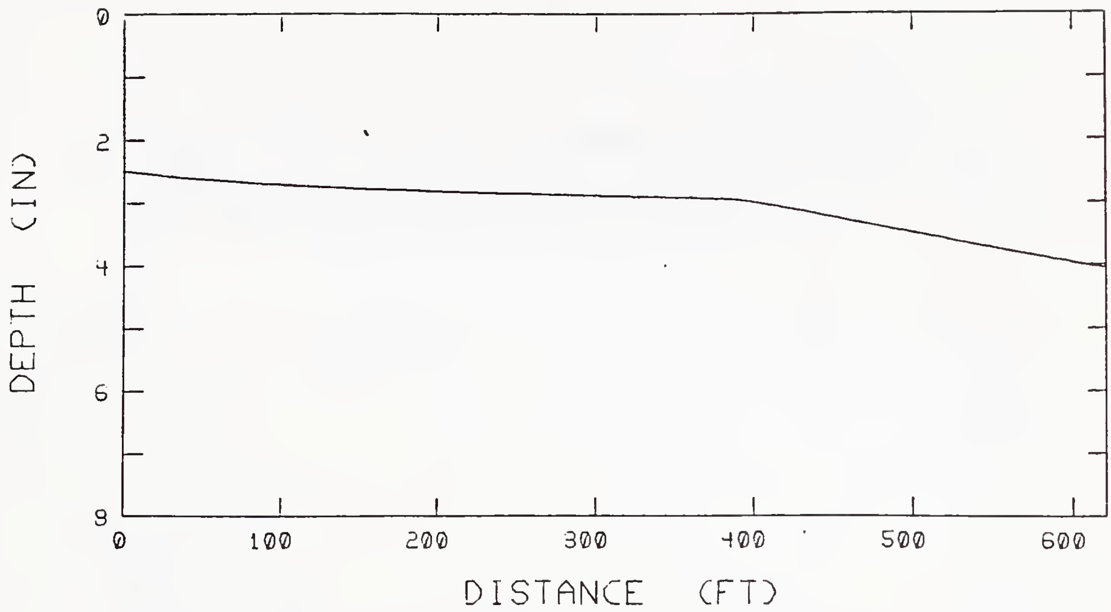


Figure 26. Advance and recession curves for CRC border #9, 8/15/79. Original volume balance constants, k = 1.994 in/hr^a, a = 0.354.

SUBSURFACE PROFILE



FLOW RATE 0.1016 CFS/FT

BOTTOM SLOPE 0.050 %

MANNING N 0.145

APPLICATION TIME 26.0 MIN.

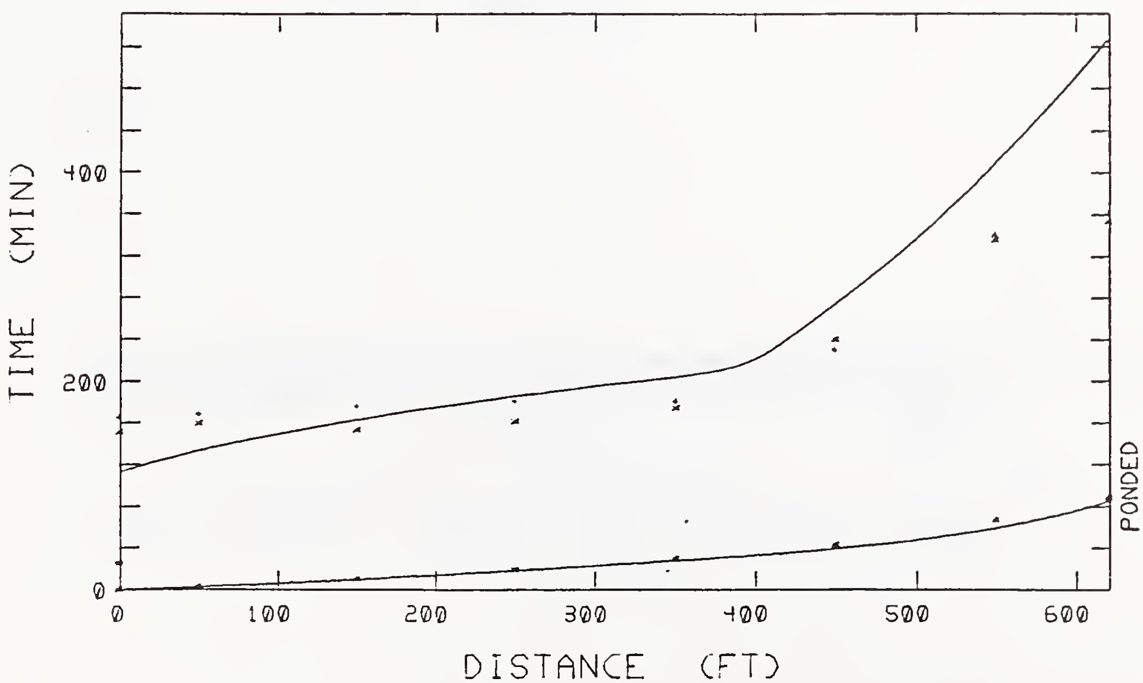
INFILTRATION CONSTANT 1.994 IN/HR**A

INFILTRATION POWER 0.354

FINAL INFILTRATION RATE 0.000 IN/HR

CRC 8-15-79 #9 1 6 11 80

ADVANCE AND RECESSION CURVES



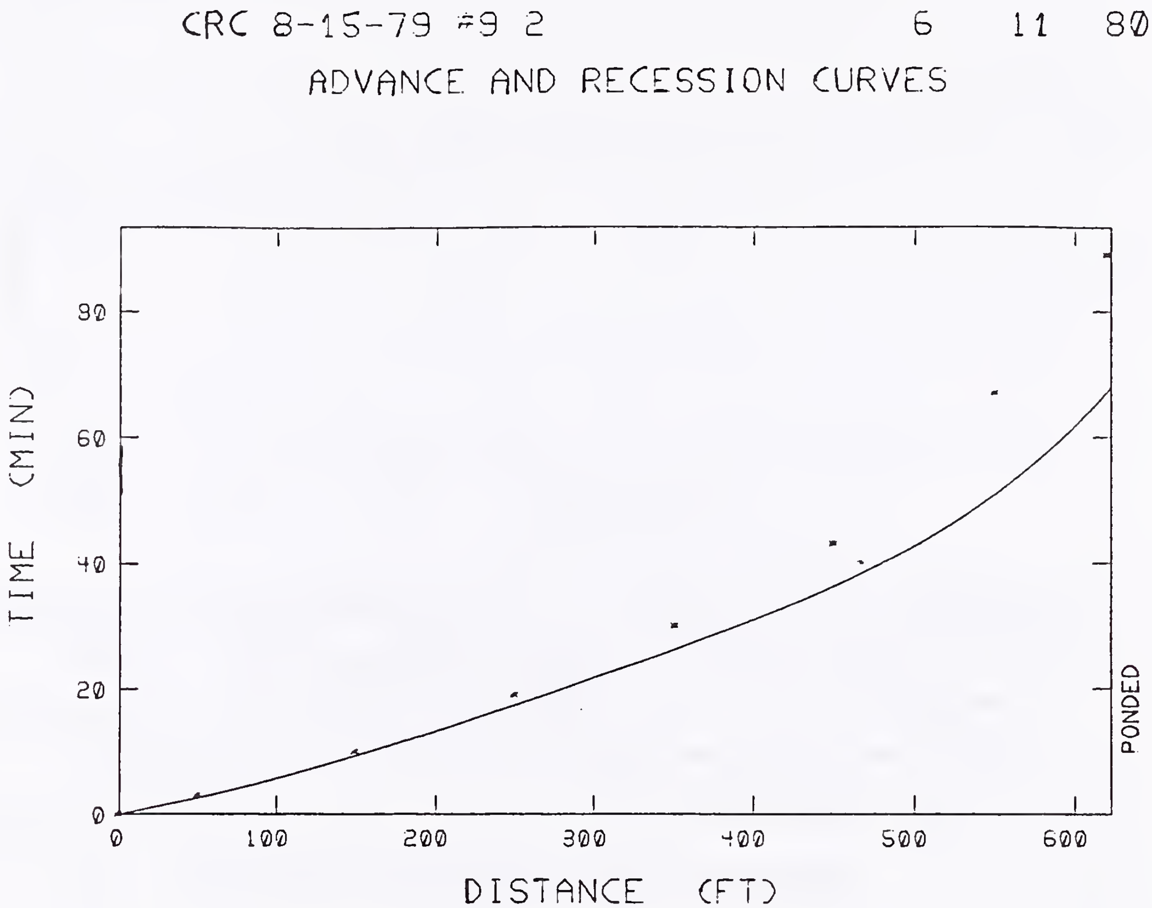
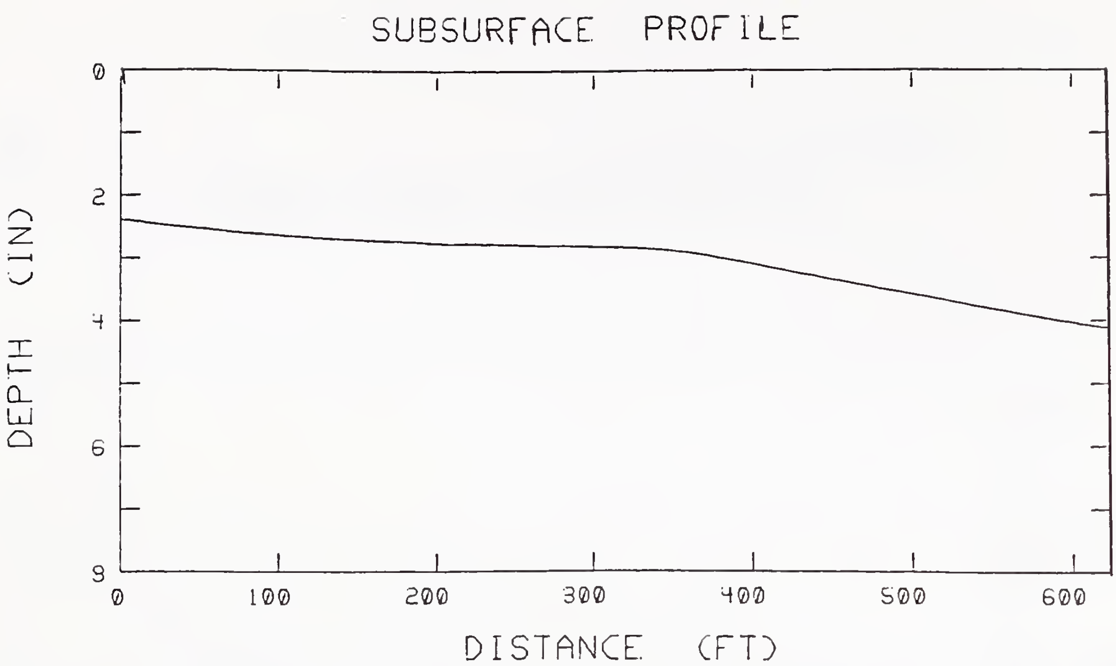


Figure 27. Advance and recession curves for CRC border #9, 8/15/79. Volume balance after 1 hour, k = 1.814 in/hr^a, a = 0.493. (Slope = 0.0001)



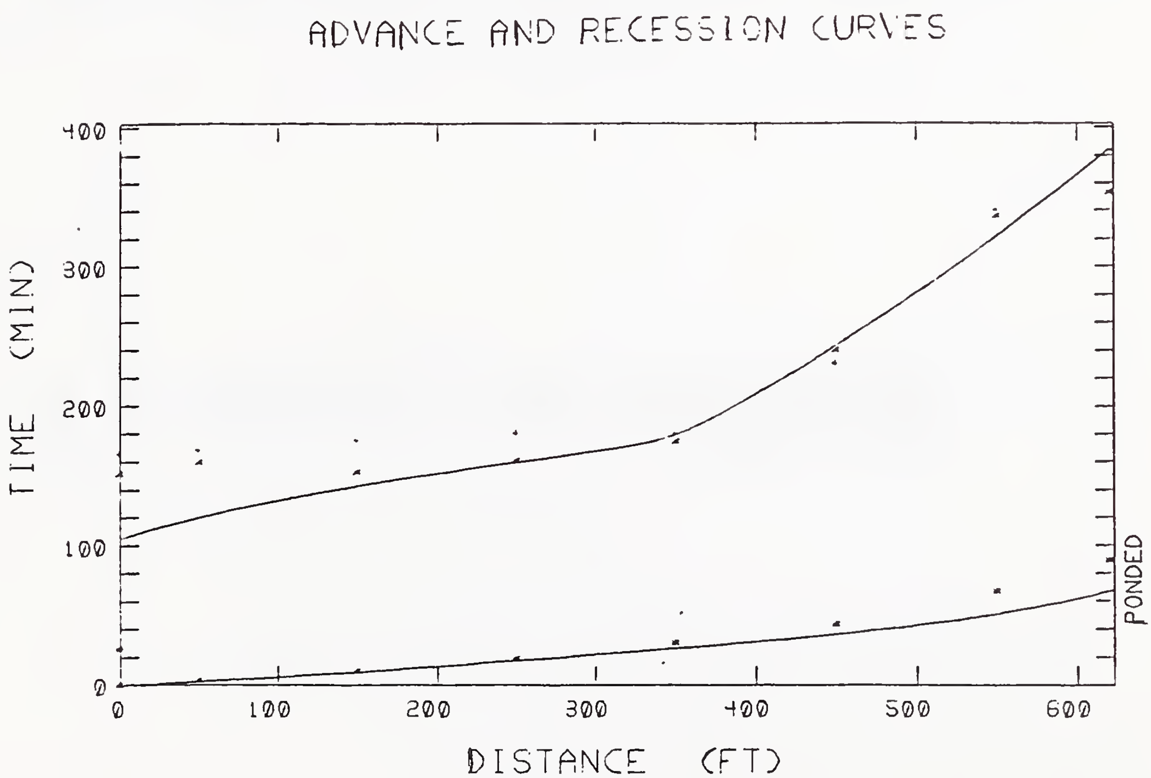
FLOW RATE 0.1016 CFS/FT INFILTRATION CONSTANT 1.914 IN/HR**A

BOTTOM SLOPE 0.050 % INFILTRATION POWER 0.493

MANNING N 0.145 FINAL INFILTRATION RATE 0.000 IN/HR

APPLICATION TIME 26.0 MIN.

CRC 8-15-79 #9 2 6 11 80



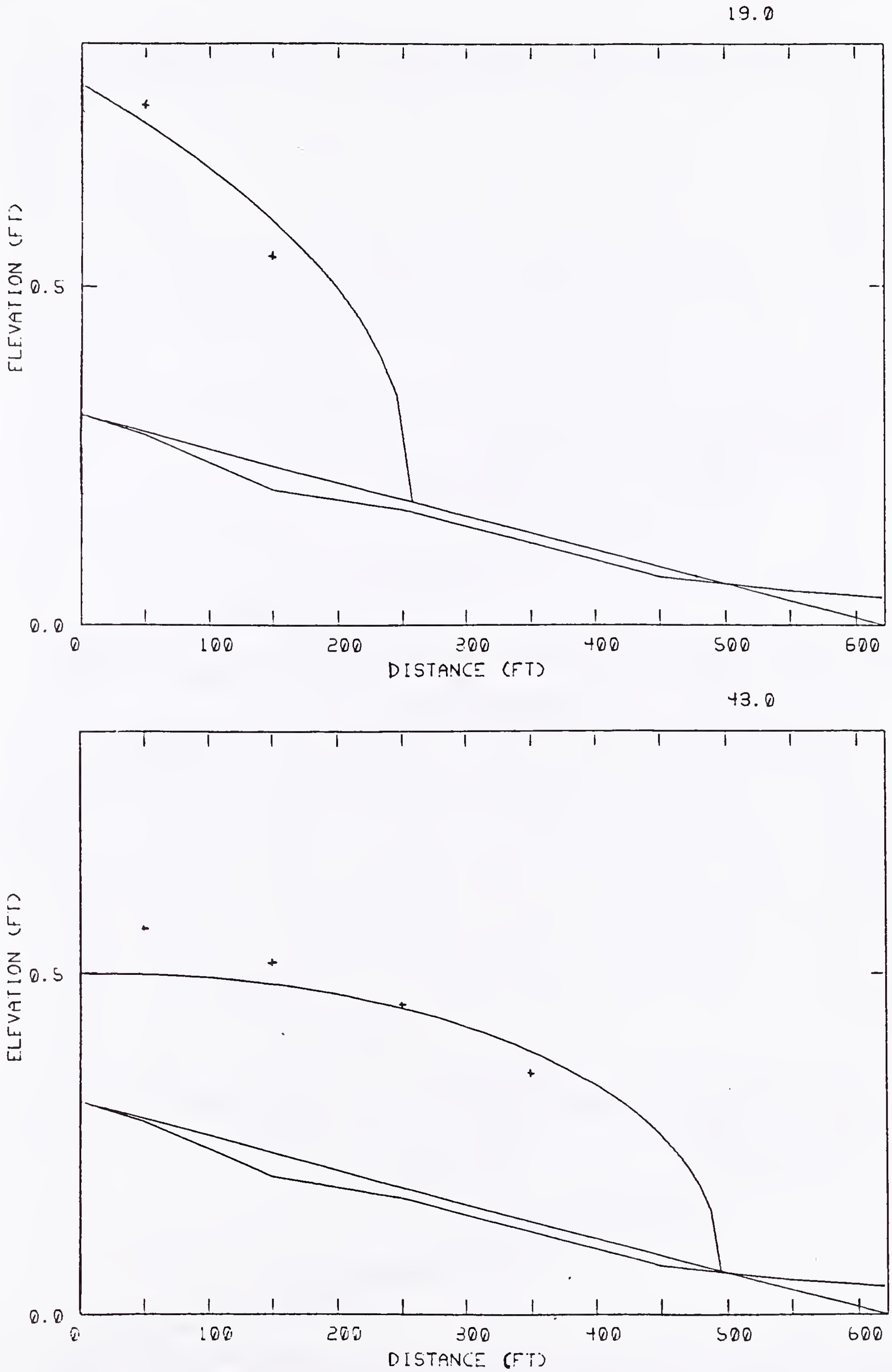
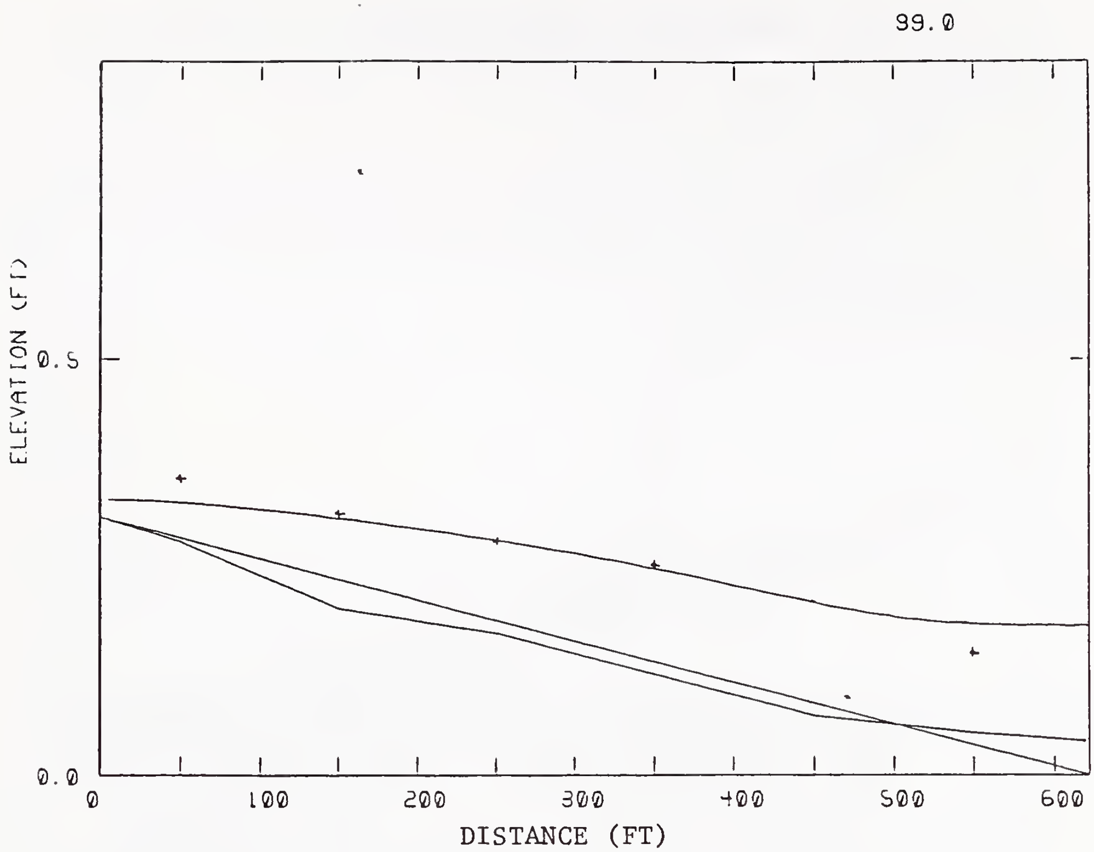
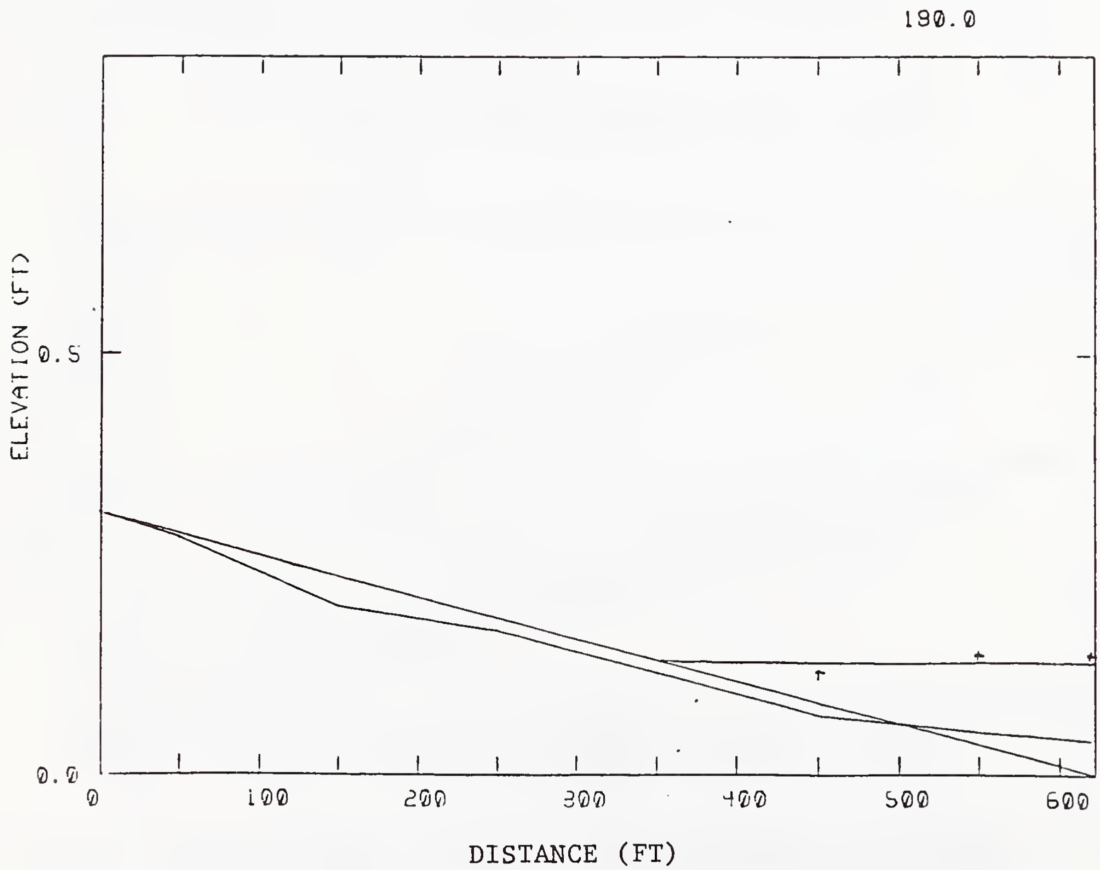
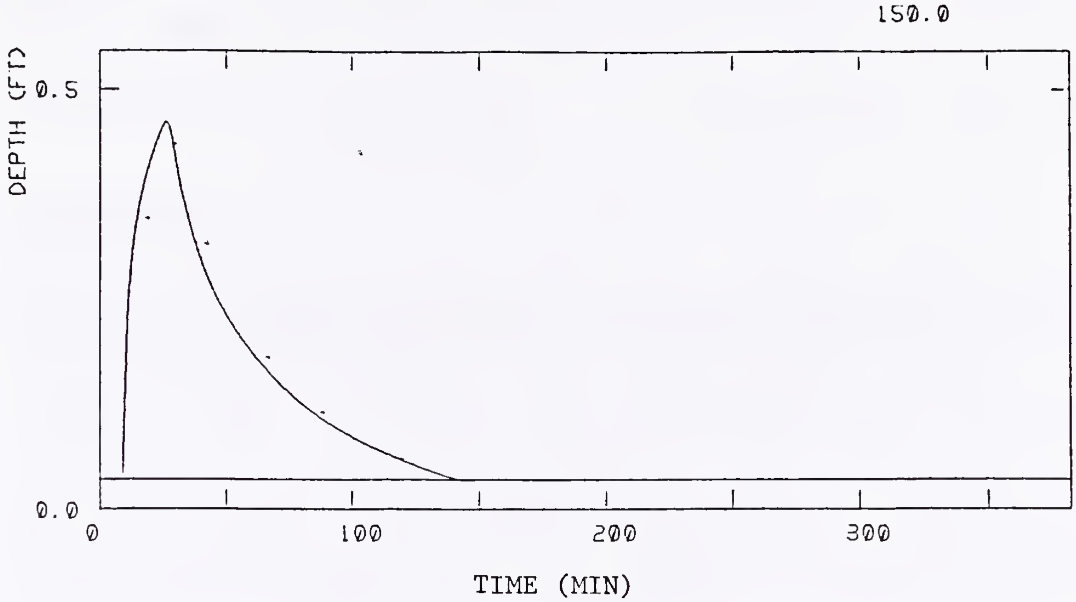


Figure 28. Profiles for CRC border #9, 8/15/79. Volume balance after 1 hour, k = 1.814 in/hr^a, a = 0.493. (Slope = 0.0001)


99.0
ELEVATION (FT)
0.5
0.0
0
100
200
300
400
500
600
DISTANCE (FT)


190.0
ELEVATION (FT)
0.5
0.0
0
100
200
300
400
500
600
DISTANCE (FT)



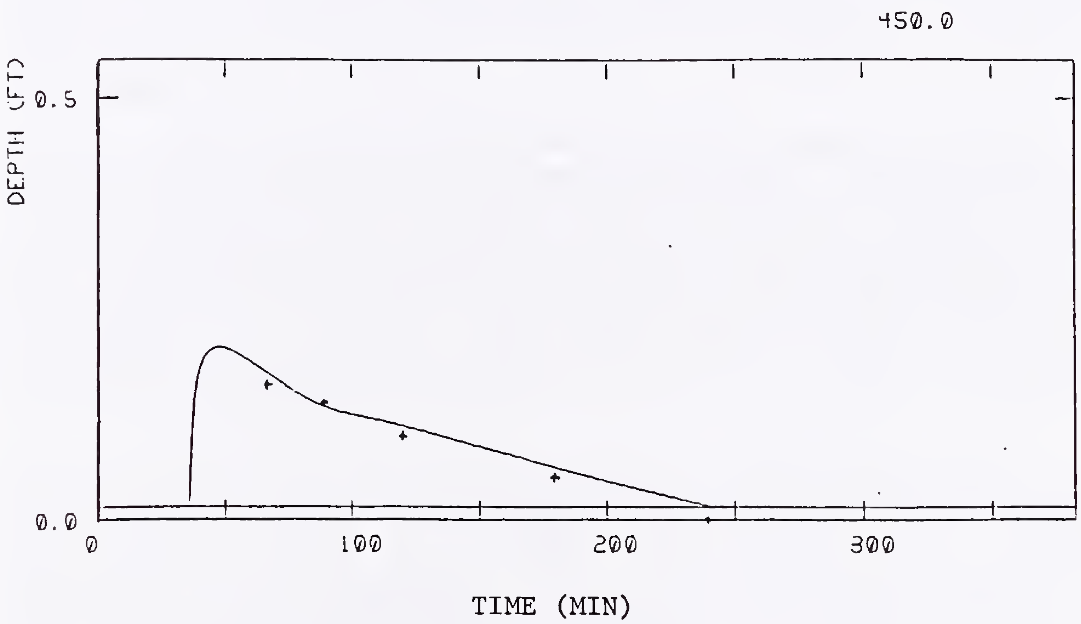


Figure 29. Depth hydrographs for CRC border #9, 8/15/79. Volume balance after 1 hour, $k = 1.814$ in/hr^a, $a = 0.493$. (Slope = 0.0001)

TITLE: CO_2 AND ENVIRONMENT EFFECTS ON PHOTOSYNTHESIS AND GROWTH OF AZOLLA

STRATEGIC PLAN: 1.3.01.1.b 50% CRIS WORK UNIT: 5422-20760-006
1.1.03.1.d 50%

INTRODUCTION

The current atmospheric CO_2 concentration is approximately 340 μL L^{-1} air and is expected to double near the middle of the next century due to the burning of fossil fuels and the extensive clear-cutting of forests (National Academy of Sciences, 1979; Carbon Dioxide Assessment Committee, 1983). In addition, the "greenhouse" effect of increased atmospheric CO_2 is predicted to result in a significant warming of the atmosphere (National Academy of Sciences, 1979; Carbon Dioxide Assessment Committee, 1983). The separate effects of CO_2 and other environmental factors on plants have been studied in detail, and recognition of the potential effects of rising atmospheric CO_2 has led to renewed interest in the effects of CO_2 on plants.

In a review of over 700 prior experiments concerning CO_2 effects on plant growth, Kimball (1985) concluded that an atmospheric CO_2 concentration of 600 μL L^{-1} would result in an average one-third increase in productivity of C_3 agronomic plants. CO_2 effects on photosynthesis have also been studied extensively. Cure (1985) reviewed the net carbon exchange rate results in 27 studies of five C_3 crop species grown for at least one week in elevated CO_2 and found an average 28% increase at 680 μL CO_2 L^{-1} air.

Little is known, however, about how other environmental variables interact with CO_2 concentration to effect plant growth. In two recent reviews, Kimball (1986) and Cure (1985) examined the interactive effects of atmospheric CO_2 and temperature on plant growth. Kimball concluded that the percentage increase in growth due to CO_2 enhancement was roughly the same over the range of temperatures at which plants are normally grown. Cure (1985), on the other hand, found that a doubling of atmospheric CO_2 resulted in generally greater increases in biomass accumulation at higher temperatures.

Most studies concerning CO_2 by environment interaction effects on photosynthesis have been of short duration with only short-term (hours to several days) acclimation to changes in CO_2 concentration. Mauney *et al*. (1979) and Delucia *et al*. (1985) presented evidence that prolonged exposure of cotton (*Gossypium hirsutum* L.) to high CO_2 produces a decline in net photosynthesis, as compared to nonacclimated plants, due to a feedback inhibition caused by starch accumulation. So, the results of some short-term experiments that have examined CO_2 by environment interactions may in some cases be misleading. The results of experiments using plants adequately acclimated to elevated CO_2 levels have not been conclusive. Campbell and Young (1986), for example, reported that a positive interaction exists between atmospheric CO_2 concentration and temperature for net photosynthesis of strawberry (*Fragaria ananasa* Duch.) acclimated for two weeks to elevated CO_2 levels. Jones, *et al*.

(1985), however, found no such interaction over a temperature range of 28 to 33°C for soybeans acclimated to 330 and 800 μL CO_2 L^{-1} air.

The genus *Azolla* is comprised of heterosporous aquatic ferns that contain a symbiotic N_2-fixing cyanobacterium (*Anabaena azollae* Strasburger) as an endophyte (Peters *et al*. 1982), and is traditionally grown as a fertilizer crop for rice in southeast Asia (Moore, 1969 and Lumpkin and Plucknett, 1980). Several studies have examined environmental effects on the growth of *Azolla* (Lumpkin and Plucknett, 1980; Lumpkin and Bartholomew, 1986), but the effects of environmental vari-ables and their interactions on *Azolla* photosynthesis have not been reported. This study was designed to investigate the photosynthetic response of *Azolla* to elevated atmospheric CO_2 and its interaction with naturally occurring seasonal changes in environmental conditions.

A further objective of this research was to establish if a relationship exists between net photosynthesis and growth rate of *Azolla*, and to determine if differences in this relationship exist between *Azolla* grown in ambient CO_2 conditions and an elevated CO_2 environment of 640 μL CO_2 L^{-1} air.

MATERIALS AND METHODS

Azolla pinnata was grown out-of-doors at Phoenix, AZ in four open-top CO_2 enrichment chambers between July 1985 and May 1986. The chambers were 2.2 m wide by 3.4 m long with 1.3 m high clear plastic walls as previously described by Kimball *et al*. (1983). Two 570 L, 1.1 m diameter polyethylene lined stock tanks were recessed into the ground in each chamber such that their tops were approximately 80 mm above ground level. The *Azolla* were grown in the stock tanks while floating in a nutrient solution described by Reddy and DeBusk (1985), but minus nitrogen, with 0.01 μg L^{-1} cobalt added as suggested by Johnson *et al*. (1966). Using the CO_2 distribution system described by Idso *et al*. (1984) and Kimball *et al*. (1983), two of the chambers were continuously maintained at a mean atmospheric CO_2 concentration of about 640 μL L^{-1} air while the other two represented ambient CO_2 conditions (approximately 340 μL CO_2 L^{-1} air).

Equal fresh weights (200 g) of *Azolla* were introduced into the stock tanks in pairs, one group into a 640 μL CO_2 L^{-1} air chamber and the other into a 340 μL CO_2 L^{-1} air chamber, at various times over the course of the experiment. At least one, but usually two or more, tanks of *Azolla* at each CO_2 level were always present and completely covering the surface of the water. The *Azolla* was removed from the tanks and replaced with fresh material when growth began to decline due to overcrowding.

Net photosynthesis of the *Azolla-Anaebaena* complex was measured weekly from 26 September 1985 to 10 May 1986 between 1130 and 1200 hours local time as follows. A 280 mm diameter by 100 mm high clear plastic cylinder, open on the bottom, was pressed through the *Azolla* mat and held in place such that it formed an airtight seal with the surface of the

water. The air in the cylinder was mixed with a 45 mm diameter 12 v fan. Two 8 cm^3 gas samples were extracted from the cylinder by syringe, the initial sample immediately after the cylinder was set in place and the final one 15 seconds later.

The CO_2 concentration in the two syringes was measured with an infrared gas analyzer (model 225-MKB, Analytical Development CO., Ltd., Hoddesdon, England[1]). The difference in CO_2 concentration was used to calculate the net photosynthetic rate. The analytical procedure closely followed that of Clegg *et al*. (1978). Three net photosynthesis measurements were taken in each stock tank on each sampling day. Measurements were conducted only on clear days.

Air temperature was monitored in each chamber with a shielded psychrometer of our own design located approximately a meter above the level of the *Azolla*. Short wave solar radiation intensity was measured approximately a meter above a nearby field of alfalfa (*Medicago sativa* L.) with a LiCor pyranometer (LiCor, Inc., Lincoln, NE, USA). The *Azolla* were removed from the nutrient solution weekly with normally submerged 1 m diameter nylon mesh screens that rigidly supported the *Azolla* in each stock tank. Fresh weights were measured using an analytical balance after the excess water had drained form the plants (Idso *et al*., 1987). Growth rates of teh *Azolla* were calculated as fresh weight gain m^{-2} surface area $week^{-1}$. A linear regression and correlation analysis was performed using the weekly growth rate as the dependent variable and the corresponding weekly net photosynthetic rates as the independent variable.

RESULTS AND DISCUSSION

Between September 1985 and May 1986 a seasonal influence was observed such that net photosynthesis in both CO_2 treatments was greater during the fall and spring and lowest during the winter months (Fig. 1). It was also observed that the relative increase in net photosynthesis due to CO_2 enhancement was greatest during the spring and fall and least during the winter.

To further explore this observation, the individual net photosynthesis responses to the 340 and 640 μL CO_2 L^{-1} air treatments on each measurement day were plotted against the mean of their responses on that day (Fig. 2). The range of mean net photosynthesis values is assumed to be reflective of the total environmental influence. A strong interaction between CO_2 concentration and environment is apparent. The difference in the two regression coefficients in Fig. 2 is significant at the 0.01 level. Under conditions where net photosynthesis was inhibited the most, it was approximately equal in both of the CO_2 treatments. When the conditions were more favorable for net photosynthesis, as indicated

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[1] Trade names and company names are included for the benefit of the reader and imply no endorsement or preferential treatment by the U.S. Department of Agriculture.

by higher mean net photosynthetic rates, the relative increase in net photosynthesis due to CO_2 enrichment increased. Under the most favorable conditions, net photosynthesis in the 640 μL CO_2 L^{-1} air treatment was approximately 70% greater than in the 340 μL CO_2 L^{-1} air treatment.

Linear regressions and correlations of net photosynthesis onto several environmental variables were conducted in order to examine their individual effects on net photosynthesis. The environmental variables used in the regressions and correlations--maximum and minimum daily air temperatures, and air temperature and short wave solar radiation intensity measured concurrently with net photosynthesis--are shown in Figs. 3-5, respectively. For all environmental variables tested, there was a significant difference ($P < 0.01$) between the regression coefficients of the 340 and 640 μL CO_2 L^{-1} air-treated Azolla, providing further evidence for an interactive CO_2 concentration by environment effect on net photosynthesis (Table I).

An examination of the correlations between net photosynthesis and the various temperature regimes indicates that net photosynthesis in the ambient CO_2 treatment was most closely correlated with the previous 9 day average minimum air temperature ($P < 0.01$), whereas net photosynthesis of the Azolla in the 640 μL CO_2 L^{-1} air treatment was most closely related to the previous 3 day average minimum air temperature ($P < 0.01$). In all cases, minimum daily air temperatures produced higher correlations than the corresponding maximum daily air temperatures for the same time period. Air temperatures recorded at the time the net photosynthesis measurements were taken were also less predictive of net photosynthetic rates than the minimum daily air temperatures. The correlations between net photosynthesis and short wave solar radiation intensity were significant for both the 340 and 640 μL CO_2 L^{-1} air treatments.

It is difficult to quantitatively separate the effects of light intensity and air temperature on net photosynthesis under natural conditions since these two variables are themselves closely related. Some general inferences can be made from the data, however.

Net photosynthesis in both the 340 and 640 μL CO_2 L^{-1} air treatments was influenced more by minimum than maximum air temperatures. This result is in agreement with previous work that showed growth rates of Azolla were affected more by minimum than maximum water temperatures (Lumpkin and Bartholomew, 1986). In our study, the previous 9 day average minimum air temperature produced the greatest influence on net photosynthesis in the 340 μL CO_2 L^{-1} air treatment, whereas the previous 3 day average minimum air temperature had the greatest effect on net photosynthesis in the 640 μL CO_2 L^{-1} air treatment. This result may indicate that CO_2 enrichment allows the Azolla to adjust or acclimate more quickly to temperature changes.

Lumpkin and Bartholomew (1986) also found that minimum water temperature exerted a greater influence on growth of Azolla than light intensity. This agrees with our results in the 340 μL CO_2 L^{-1} air treatment, where

net photosynthesis was more highly correlated with the previous 9 day average minimum air temperature than with the intensity of short wave solar radiation (Table 1). The situation is reversed, however, in the 640 µL CO_2 L^{-1} air treatment, where net photosynthesis was influenced more by light intensity than air temperature (Table 1). Light saturation for the growth of Azolla has been reported to occur at relatively low levels, approximately 375 W m^{-2}, under ambient CO_2 conditions (Lu et al., 1963 as cited in Lumpkin and Plucknett, 1980). For Azolla grown in higher CO_2 concentrations it appears that the light saturation point must be higher due to the increased capacity for CO_2 fixation. Similar results have been found during CO_2 enrichment of strawberries (Campbell and Young, 1986).

The linear relationships between growth rate and net photosynthetic rate of the Azolla in both the ambient CO_2 treatment and 640 µL CO_2 L^{-1} air treatment are shown in Fig. 1. A significant coefficient of determination was found for this relationship in both CO_2 treatments ($P < 0.01$) and may indicate a potential use for net photosynthesis as a tool for predicting growth rate of Azolla. This result is also of interest because a distinctive lack of correlation between growth and photosynthesis per unit leaf area has resulted from studies that have examined this relationship for many other plant species (Elmore, 1980; Delaney and Dobrenz, 1974a, 1974b, 1981).

The probable reason that this relationship is significant in this particular study is that the growth rate and net photosynthesis measurements were taken over a wide range of environmental conditions which allowed for a wide range of growth rate and net photosynthesis responses. For example, there was more than a five-fold difference between the lowest and highest net photosynthetic rates. Most other studies which have attempted to correlate growth and photosynthesis have been conducted in a smaller range of environmental conditions.

There was not a statistically significant difference between CO_2 treatments for their regression coefficients (shown in Fig. 1) resulting from the regression of growth rate onto net photosynthesis. This result indicates that the Azolla in both CO_2 treatments responded similarly in terms of fresh weight accumulation per unit of net photosynthetic activity through the entire range of environmental conditions which they encountered in this experiment.

CONCLUSION

This research presents strong evidence in support of a CO_2 concentration by environment interaction effect on photosynthesis of Azolla. These interactions have not been studied extensively in other plant species, but may very likely exist, particularly for C_3 species which lack the internal CO_2 concentrating mechanism of C_4 or CAM plants.

This research may also explain in part the wide range of responses to CO_2 that have been reported under steady state environmental conditions (Cure, 1985; Kimball 1985 and 1986). In environments representing low

photosynthetic potential, the effects of CO_2 enhancement may be underestimated as compared to studies conducted in conditions that promote optiumum photosynthetic rates. This same reasoning may also apply to plant growth responses to CO_2, but requires further investigation. Furthermore, studies which attempt to predict plant responses to the rising atmospheric CO_2 concentration must consider the effects of concurrent changes in other environmental variables such as solar radiation and temperature.

A clear and significant linear relationship was established between growth rate and net photosynthetic rate of Azolla, although attempts to establish this same relationship with many other plant species have failed (Elmore, 1980). There is no apparent CO_2 concentration by environment interaction effect on the amount of growth per unit of photosynthetic activity. It can be assumed, then, that the efficiency of the biochemical conversion of photosynthate into biomass accumulation is not affected by CO_2 concentration of a CO_2 concentration by environment interaction.

ACKNOWLEDGEMENTS

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PERSONNEL

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Table 1. Linear correlation (r) and regression (b) coefficients for relation ship between net photosynthesis (Pn, μMol CO_2 m^{-2} s^{-1}) and environmental variables.

Environmental Variable	CO_2 Treatment (μL L^{-1} air)	r	b	n-2
Short wave Solar radiation	340	0.52**	0.007a[2]	27
($W\ m^{-2}$)	640	0.85**	0.022b	27
Ta[1] (°C) at time	340	0.21	0.094a	27
of Pn measurement	640	0.57**	0.505b	27
Previous 24 hour	340	0.31	0.173a	27
minimum Ta (°C)	640	0.62**	0.691b	27
Previous 24 hour	340	0.16	0.065a	26
maximum Ta (°C)	640	0.53**	0.438b	26
Previous 3 day average	340	0.46*	0.251a	27
minimum Ta (°C)	640	0.68**	0.754b	27
Previous 3 day average	340	0.29	0.117a	27
maximum Ta (°C)	640	0.56**	0.454b	27
Previous 6 day average	340	0.54**	0.317a	26
minimum Ta (°C)	640	0.66**	0.742b	26
Previous 6 day average	340	0.37*	0.155a	27
maximum Ta (°C)	640	0.60**	0.500b	27
Previous 9 day average	340	0.62**	0.402a	26
minimum Ta (°C)	640	0.66**	0.806b	26
Previous 9 day average	340	0.44*	0.193a	27
maximum Ta (°C)	640	0.59**	0.519b	27

1 Ta = Air Temperature.

2 b values within each cell followed by same letter not significantly different at 0.01 level.

*,** r values significant at 0.05 and 0.01 level, respectively.

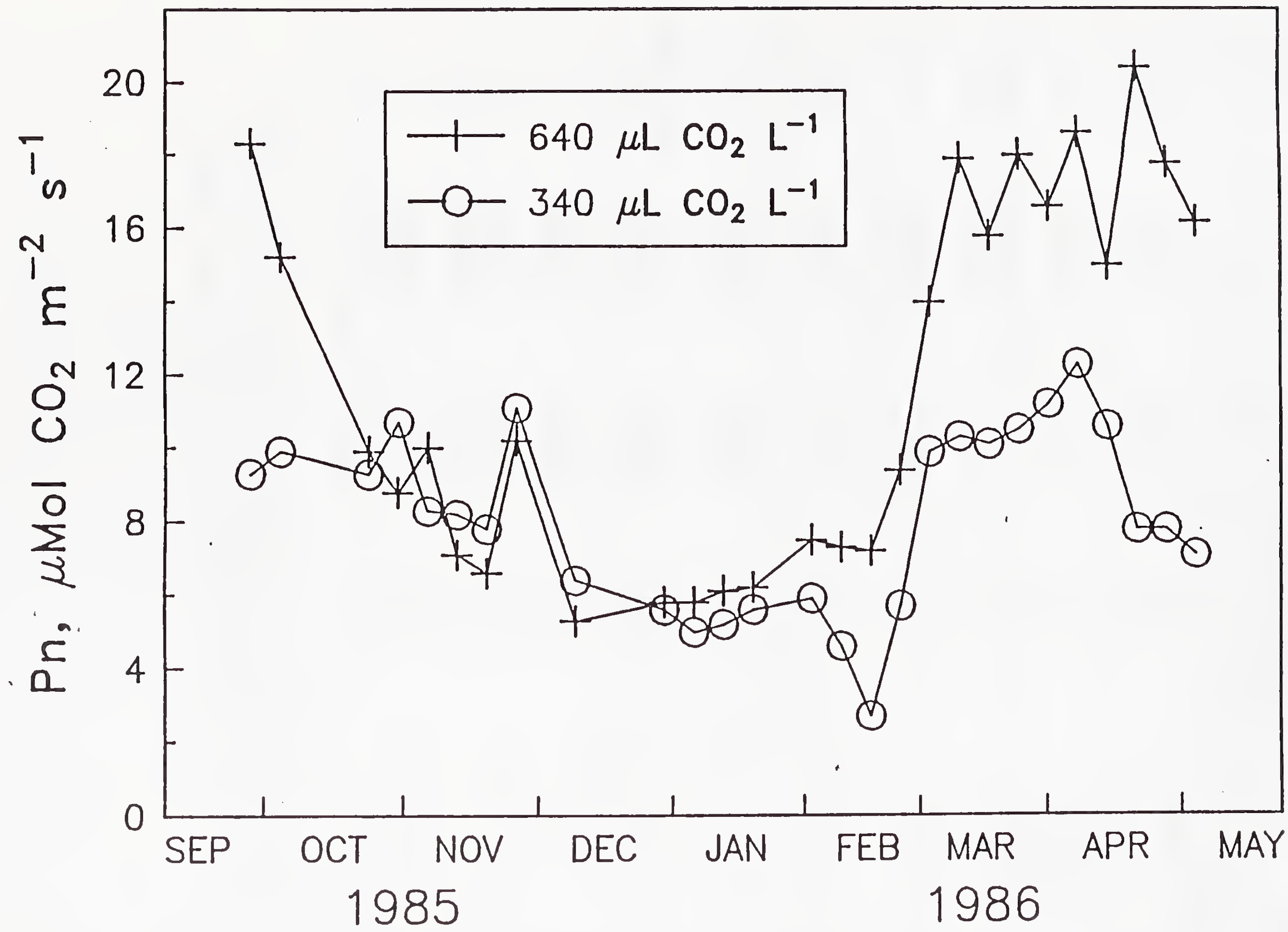

Fig. 1. Net photosynthesis (Pn) of Azolla grown continuously in 340 or 640 µL CO_2 L^{-1} air between 26 September 1985 and 10 May 1986. Measurements made between 1130 and 1200 hours local time.

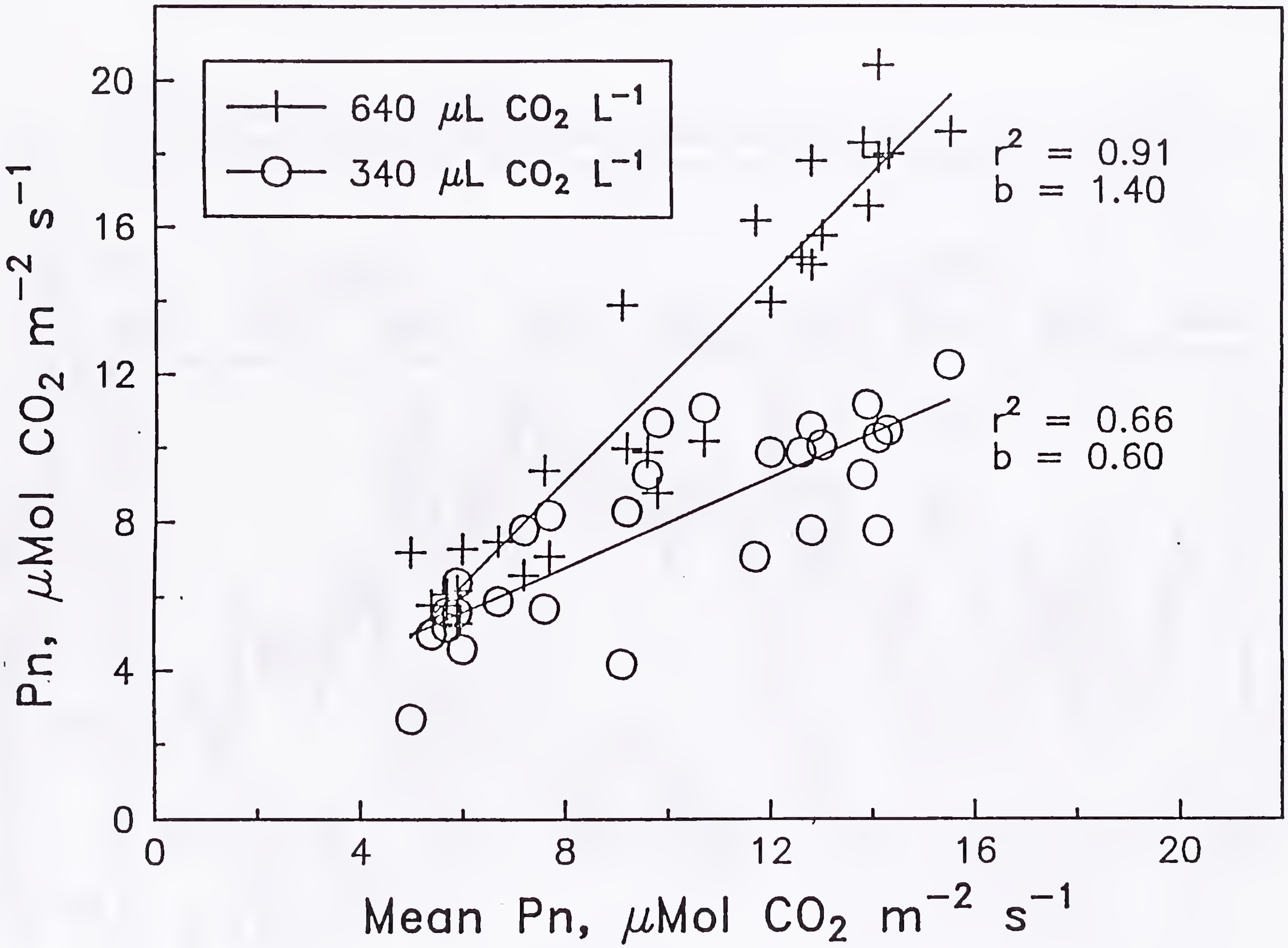

Fig. 2. Linear regression of individual photosynthetic rates of 340 and 640 μL CO_2 L^{-1} air-treated Azolla onto their mean net photosynthetic rate. Coefficients of determination (r^2) for both curves are significant at the 0.01 level. Regression coefficients (b) of the two curves are significantly different at the 0.01 level; n = 29.

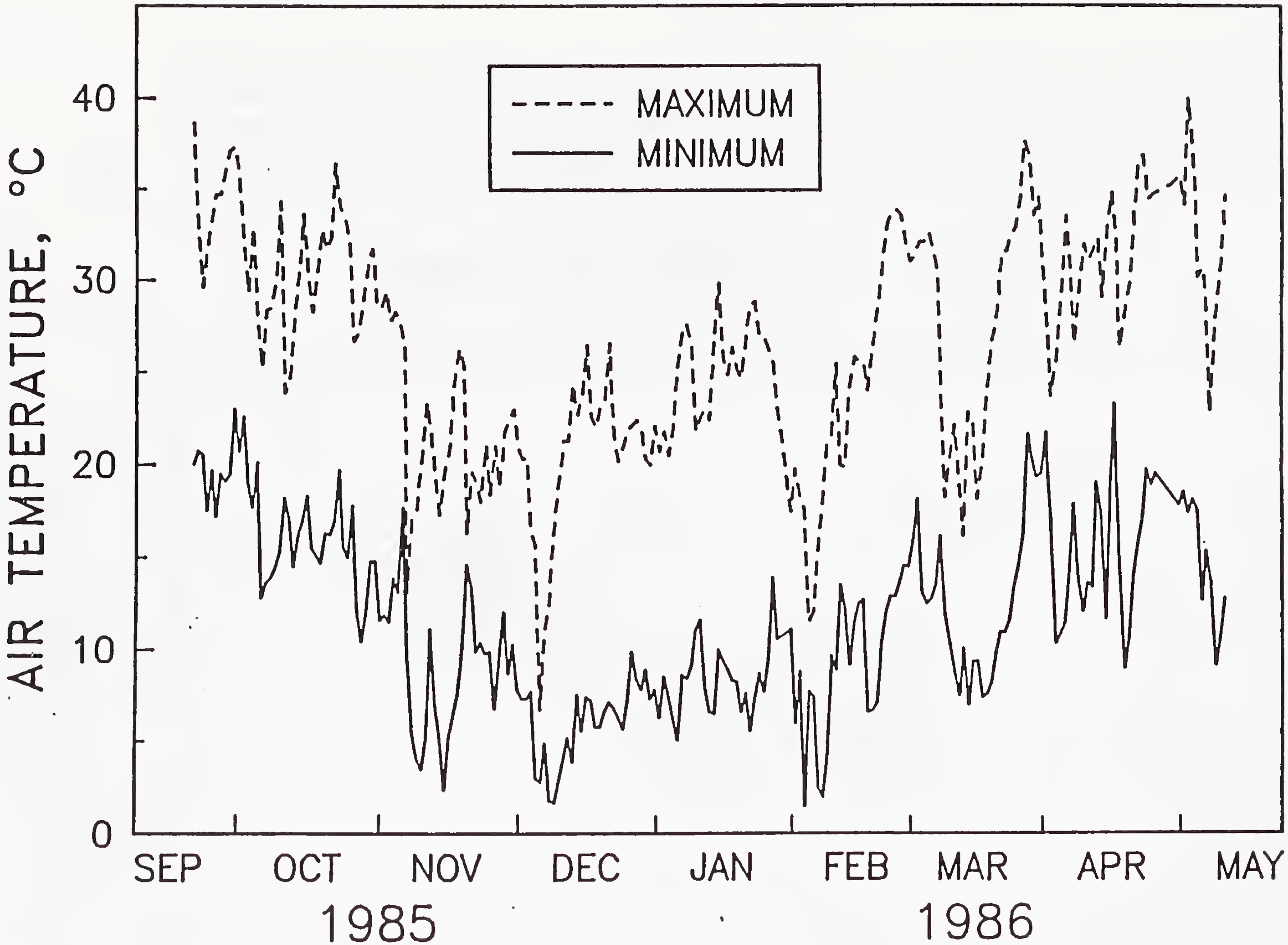

Fig. 3. Daily maximum and minimum air temperatures between 26 September 1985 and 10 May 1986. Values represent the mean of temperature measurements made in each of the four CO_2 enrichment chambers.

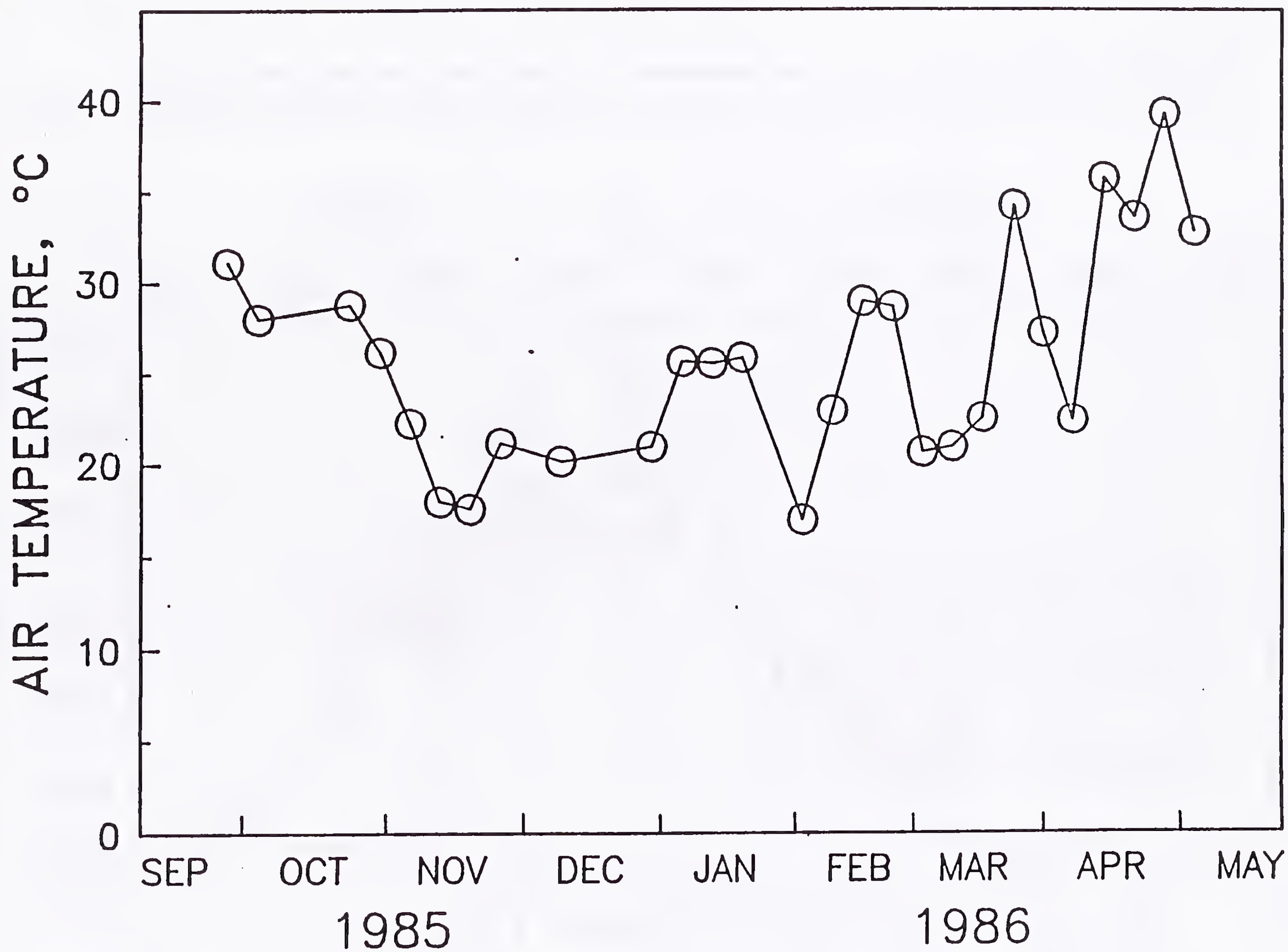

Fig. 4. Mean air temperatures recorded between 1130 and 1200 hours local time on days that net photosynthesis measurements were conducted.

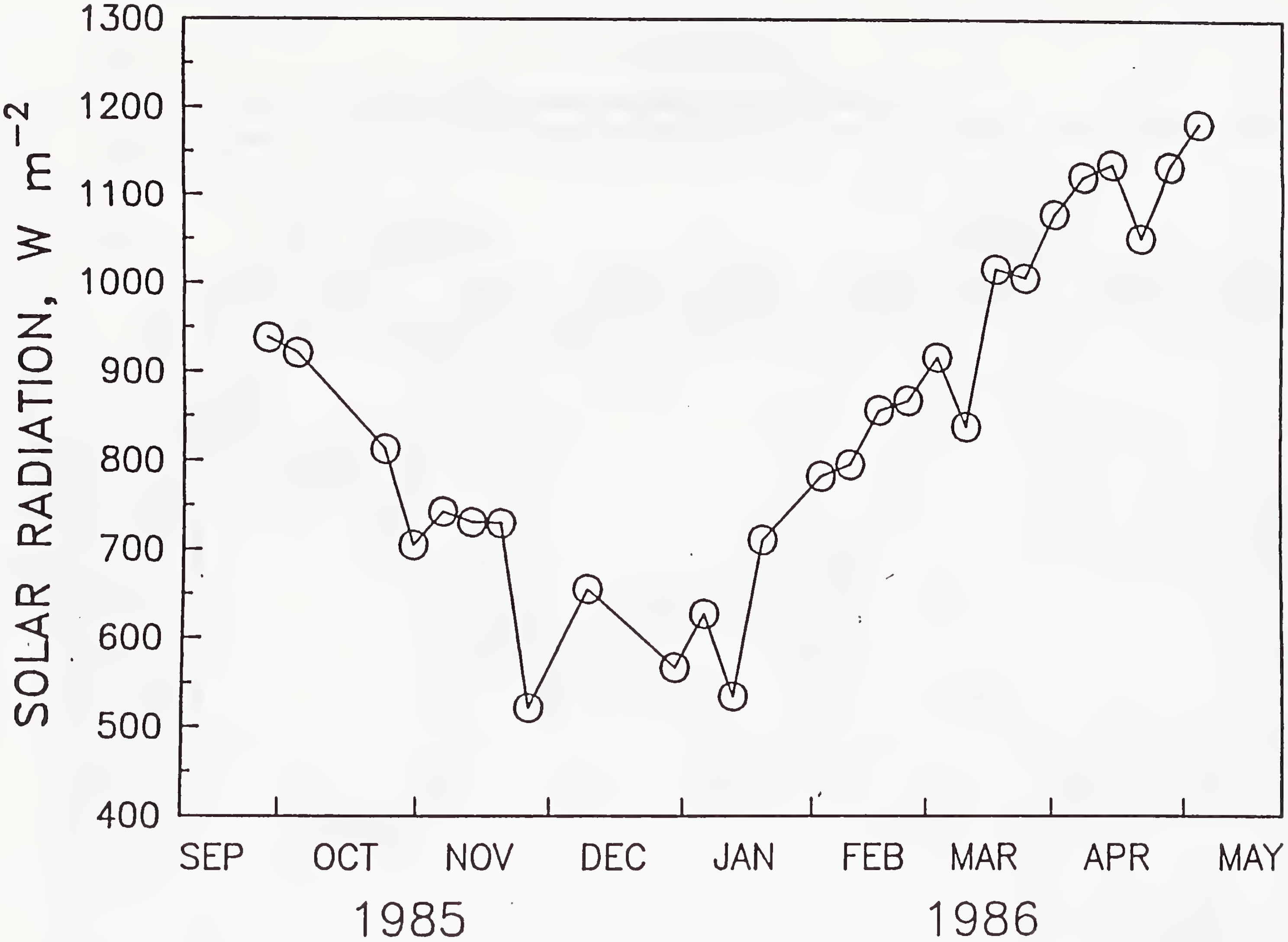

Fig. 5. Average short wave solar radiation intensity measured between 1130 and 1200 hours local time on days that net photosynthesis measurements were conducted.

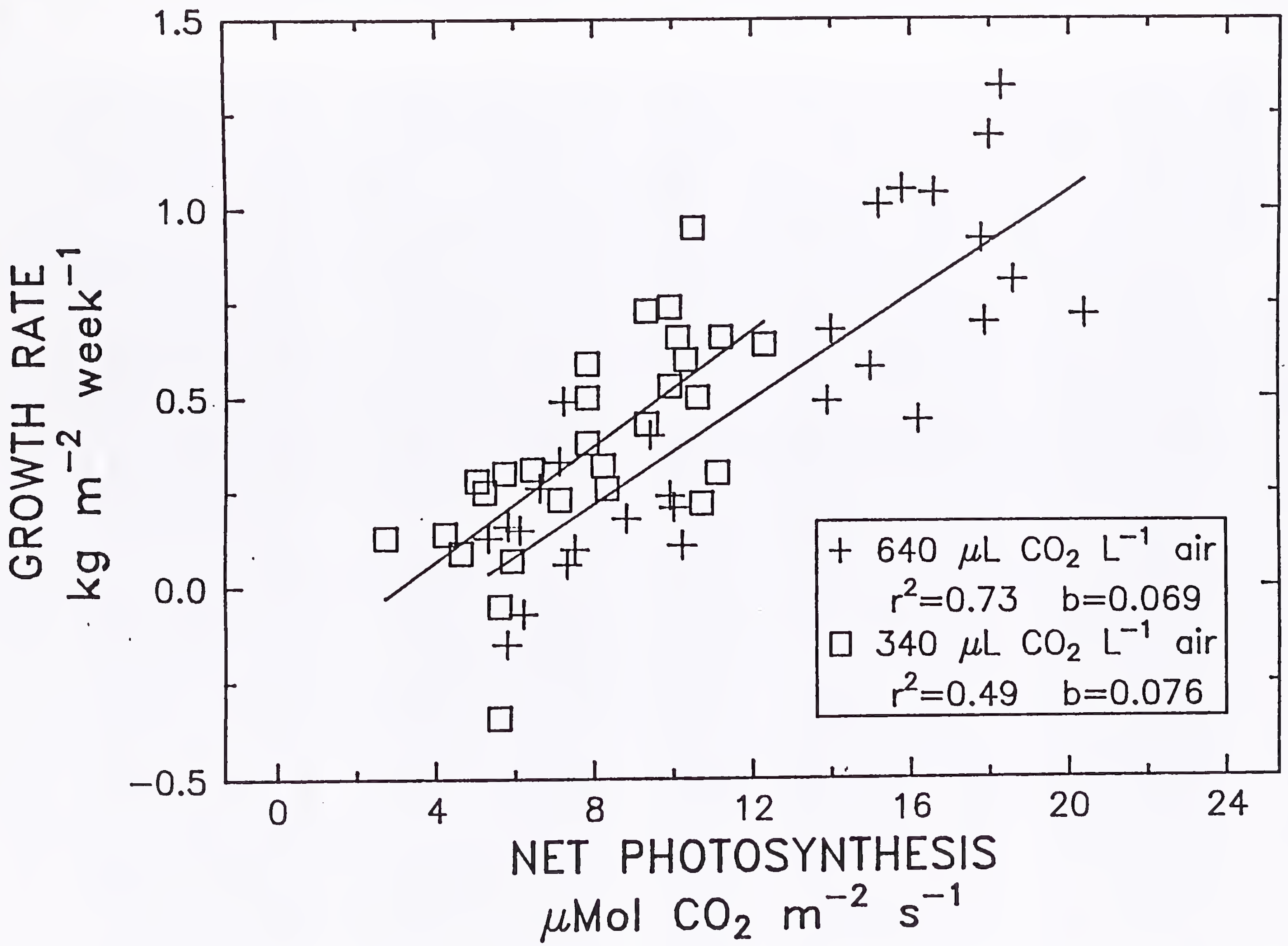

Fig. 6. Linear relationship between weekly-measured growth rates and net photosynthesis rates of Azolla grown in 340 and 640 μL CO^2 L^{-1} air between September 1985 and May 1986.

TITLE: SEEDLING ESTABLISHMENT OF NEW CROPS UNDER CRUSTING AND OTHER LIMITING SOIL RELATED CONDITIONS

STRATEGIC PLAN: 1.2.03.1.a 70% CRIS WORK UNIT: 5422-20760-007
2.3.04.1.n 30%

INTRODUCTION

A number of new crops have been proposed for commercialization to help revitalize U.S. agriculture or to supply strategically needed raw materials. Success for any of them depends on the proper linking of a host of complicated factors which range from economic, to political, to technical. One of the most critical links in the process is simply to be able to successfully and inexpensively establish the new crops by direct seeding.

Guayule, one of the new crops under evaluation, is difficult to establish using direct seeding because the seeds and seedlings have low vigor: low and prolonged germination, many abnormals, and slow growth during the establishment phase. This makes the seedlings vulnerable for an extended period of time to drought, salt, high radiation/temperature, blowing sand, disease, various herbivores, and weeds. Also, small seeds such as guayule require greater sophistication of equipment and operator skill for planting than that required for traditional large seeded agronomic crops.

Because of these difficulties, guayule field plantings generally have been established from transplants. This is costly and time consuming (Bucks et al., 1985).

Several researchers have attempted to direct-seed guayule this past half century. There was agreement by researchers that guayule should be planted shallow in soil (Hanson, 1944, Taylor 1946; Naqvi and Hanson, 1980; Bucks et al., 1985), and that the young plants are extremely sensitive to water and salt stress (Miyamoto et al., 1984; Bucks et al., 1985). Fresh seed seems to have a light requirement for germination, but this is negated by conditioning with gibberellins (Chandra et al., 1985). Germination of fresh seed is highly temperature dependent, but this requirement is relaxed considerably by conditioning (Chandra et al., 1985).

These findings present conflicts. Deep plantings normally should provide the most favorable environment for germination; i.e., lower water and salt stress and moderated temperature compared to surface plantings. It is the soil surface that is most subject to rapid drying, salt accumulation, temperature extremes, and crusting. The problem with guayule, and most small seeded crops, is that they are too weak to push through much soil, and particularly through an environmentally unfavorable surface layer. The challenge then is to place the seeds as deep in the soil as possible and then somehow aid the plant in its upward journey. Various possibilities exist.

The overall objective of these new-crop establishment studies is to develop management techniques to get the seedling up as fast as possible, with as uniform a stand as possible, and under as adverse conditions as possible (soil moisture, salt and temperature), and with as little irrigation water as possible, and with a minimum of labor, equipment, and other costs. The objectives of this particular direct-seeding study were to determine if guayule would germinate and emerge if planted in the soil rather than on the surface, to evaluate benefits of seed clumping vs. singulation, and to evaluate establishment as a function of soil water availability. Several pest control measures had to be added to save the experiment.

MATERIALS AND METHODS

The experiment was carried out in the laboratory's 24 x 2.5 m uncovered, plastic-lined sand pit. The site was rototilled, leveled, and smoothed. Two side-by-side drip lines, (20 cm hole spacing on each), were installed down the middle (Fig. 1). Water applications (Phoenix City) were controlled with a timer and pressure regulator.

The experiment was a split plot design (Fig. 1). Three "fixed" water levels were obtained by planting rows 3, 13, and 23 cm from the edge of the drip line. Actually, the lines were fixed, but, as would be expected, the soil water content varied slightly along each row. The 4 seed placement treatments (singulated-surface, singulated-5mm deep, clump-surface, and clump-5mm deep) were randomized within each of the 4 replications. Rows for each seed placement treatment were 2 m long. One hundred seeds were randomly spaced for the two singulated treatments (surface and 5 mm deep placement), and 20 clumps of 10 seeds each spaced 10 cm apart for the 2 clumping treatment (also, surface and 5 mm deep). A board fitted with 8 mm diameter dowls was used to punch the holes for the 5 mm-deep clumping treatment, and a board fitted with a piece of sheet steel was used to punch a trough for the 5 mm-deep singulated treatment. Seeding was done when the soil was moist to avoid sloughing.

The plot was seeded September 11, 1986, using guayule cv. 11591, which had been conditioned (Chandra and Bucks, 1985) on August 18, 1986, by G. R. Chandra of the USDA-Plant Genetics and Germplasm Institute, Beltsville, MD.

Stand counts (emergence and survival) for all plants and for clumps were taken every day for the first week, then periodically thereafter until day 43 (6 weeks) when the study was terminated. Plant and clump spacings of survivors were determined at the end of the study. Plant lengths (root plus shoot, and shoot alone) were determined on approximately 10 randomly selected plants per treatment-replication. All available plants were evaluated on those treatments having 10 or less plants. Average plant weights (50 C) also were determined on these harvested plants.

Soil moisture aspects: the amount of water applied was metered, and rainfall events recorded; the visible wetting front, perpendicular to

the drip line was measured several times early in the morning and in the afternoon following peak evaporation; soil moisture samples were taken initially prior to planting and periodically during emergence at 0-5 and 5-10 mm depths from 0 to 35 cm, in 5 cm increments, perpendicular to the drip line. After emergence, sampling depths were changed to 0-1 and 1-6 cm.

Salt content of the irrigation water was determined periodically with a conductivity bridge. Soil salt content was determined before, during (day 7) and at the close of the study. The day-7 samples were composited from the replication-treatments taken at 0-5 and 5-10 mm depths directly from the 3 rows. Those at termination were taken similarly but at 0-5 and 5-60 mm depths. Soil salts were determined using both 1 to 1 and saturation extracts, according to procedures outlined in the Salinity Handbook (1954). Water activity over a range of water contents was determined on several of the above soil samples using thermocouple psychrometers (Wescor, Inc., Logan, UT).

Other measurements: The seed was tested for germination (Appendix A). A few soil temperature and penetometer readings were taken. Replications 2 and 4 were fertilized two times, on days 21 and 36, with a complete water soluble nutrient solution (92.2 g Peters Professional Hydro-Sol (5-11-26) and 61 g calcium nitrate (15.5-0-0) per 95 ℓ water. The nitrogen application rate was 1 kg N per ha per application.

Pests: Since pest control was not part of the original experimental design, this aspect is covered separately in Appendix B.

RESULTS AND DISCUSSION

Soil Moisture

The irrigation schedule observed the first 11 days after seeding (6 hrs. each day) produced the visible surface wetting front shown in Fig. 2. The rather sharp line between wet vs. dry soil was wavy, but almost always extended beyond the middle row of plants. During the evening the front would extend to cover most of row 3, but would retreat during the day leaving most of the surface of row 3 in an air-dry state.

Actual soil moistures during the germination/emergence stage are shown in Fig. 3. During irrigation the near saturated water content at row 1 (3 cm from drip line) exceeded 17% for both the 0 to 5 and 5 to 10 mm depths. Water content rapidly decreased with distance from the line, dropping to between 11 and 12% at row 2, and between 6.5 and 7.5% at row 3. Moisture contents at the two soil depths at each row during irrigation were nearly identical (<1.5% difference).

The bottom set of symbols in Fig. 3 shows the soil water content after the soil was allowed to drain and dry for a half day. Water content at rows 1 and 2 dropped dramatically, but there was only a slight reduction at row 3. As during irrigation, there was not much difference in water content between the 0-5 and 5-10 mm depths. There was only about a one

percent difference in water content between the first and second rows, and less than another 2% difference between the second and third rows; i.e., only a 3% spread in water content between the 3 rows. As will be evident from the emergence/stand data, these slight differences in water content apparently greatly affected the water activity around the germinating seed and emerging seedling.

After day 11 irrigation frequency was cut back to allow the surface soil near the drip line to dry out. By that time there was visual evidence that plants nearest the drip line were receiving too much water (off color and slower growth). Figure 4 shows the soil water contents of the 0-1 and 1-6 cm depths with extended drying times. Now, as compared to when the plot was irrigated daily, there were fairly large differences in water content between the two evaluated soil layers (5% by day 4 for all three rows). By day 4 the water content of the surface centimeter of soil had essentially reached a minimal value of 0.5%. The 1-6 cm layer continued to dry as the period between irrigations was extended to 7 days (the maximum time between irrigations), reaching a low value of about 4%.

There was almost no difference in water content between the 3 rows at the 2 depths by day 4. Any water mound formed under the drip line was quickly dissipated in this sand after irrigation was terminated.

An interesting observation from Fig. 4 is the convergence of the water content lines to the dry row 3. The spread between the period when irrigation is in progress and after 4 days of drying is only about one percent water 6 vs. 7%) at the 1-6 cm level. This assumes near constant water contents throughout the upper profile during and shortly after irrigation so that the difference in sampling depths can be ignored.

Salt Content

The irrigation water applied averaged 433 $\pm$ 38 ppm salt. This was good-quality, treated Salt River water.

Salt content (conductivity) of the soil after the first week and at the end of the experiment, as determined with a 1:1 extract, is shown in Fig. 5. Salt content of the rototilled soil at the start of the soil was 8.5 dSm^{-1}, so during the course of the experiment salt apparently was removed from all 3 rows. As expected, most of the salt near the drip line was washed away when irrigation started, and apparently was washed to such a great depth that very little was pulled back up to the surface by capillary action during the extended drying periods near the close of the experiment. Salts increased with distance from the drip line and most of that salt accumulated at the soil surface.

The salt contents also were determined using the saturation extract method. A linear regression of the 1:1 (y) vs. saturation extract (x) data gave a slope of 0.817, a y-intercept of -0.025 and a correlation coefficient of 0.9668. The slope (<1) merely shows that the salt content of the saturation extracts is greater than that of the 1:1

extracts. In a finer textured soil the saturation extract method may more closely duplicate conditions as the root experiences them; but in a sand like this, conditions near the root are rather indefinite.

We attempted to measure the water activity of the soil. Figure 6 shows a great difference in activity of surface (0-5 mm) vs. deeper (5-60 mm) soil taken from row 3 at the close of the experiment. Activity increased logarithmically as water content decreased. At approximately 6 to 7% water (the water content of row 3 during germination/emergence) the activity of the water was 9 to 10 bars.

Emergence/Stand

The most surprising and encouraging findings of the study was the ease and quickness of seedling emergence from the 5 mm deep plantings. By day 2 the seedlings were emerging rapidly from the sand (Figs. 7 and 8), and by day 6 the germination and emergence phases of establishment were completed -- at least for the two wettest treatments.

Contrarywise, the surface planted seeds had near zero germination. We had expected just the opposite; i.e., rapid establishment on the surface plantings and low, prolonged emergence on the 5-mm deep treatments.

Maximum emergence for the two singulated, wet, 5-mm deep plantings was 55% and 47% respectively for the 3 and 13 cm spaced rows, respectively. These represent 76% and 65% of the potential germination (Appendix A). This is good emergence for guayule, but does not begin to compare with the 90% or higher values expected of common horticultural crops such as lettuce (Pauli and Harriott, 1968).

Less than 10% of the deep planted seeds in the dry (23 cm), singulated treatment germinated initially, although a few more emerged after a rain on day 12.

Stands of the deep planted clumps were the most promising of all (Fig. 8). By day 5, 95% of the clumps on the wettest treatment had emerged; i.e., at least one plant present in each clump.

Emergence reached 98% for that treatment, if one disregards the one replication which was heavily browsed by ants the first night (Appendix B). Even the driest treatment (23 cm row) had plants at 50% of the clump sites after one week; this jumped to over 60% after the first rain.

Individual plants in the clumping treatments also were counted (open symbols, Fig. 8), but crowding made this difficult. Individual plant counts (percent) were less than for the singulated treatments. One must remember that the actual seed planting density for the clumping treatments was twice that for singulation (200 vc. 100 seeds per 2 meter row).

Germination and emergence clearly benefited from the low water tension and activity of row 1. Even through the difference in water content between the 3 rows was slight, this difference was sufficient to significantly affect emergence (Table 1; significant at P = 0.01).

The plot was maintained for 43 days (6 weeks) to obtain a measure of survivability of the individual young guayule plants and of the clumps (Figs. 7 and 8, Table 2). Results in Table 2 are listed 1) on the basis of number of seeds planted; 2) as adjusted for expected germination (parentheses); and 3) as losses compared to the stands on day 7 [brackets]. Losses of 10 to 30% may seem high, but these actually are low compared to what has been observed in most field plantings. Clumps survived best, with only a 4% loss and a 2% gain for the wettest and driest rows, respectively. After 6 weeks, 90% of the planted clumps on the wet 5-mm deep treatment had surviving plants. Since the stands remained relatively constant over the period of study, the differences due to water content, the treatments and the interaction also continued to show significance at the .01 level (Table 1).

Figures 7 and 8 show initiation of rates of rapid declines in the stands of most treatment/rows during the third week. This was mostly due to insect damage. Several insecticides were tried but finally insects were brought under control with Spectracide (see Appendix B for details). Plant stands for most treatments remained fairly stable after the Spectracide application.

Plant Length

Table 3 shows the average plant lengths (roots plus shoots) for the two treatments, singulated-deep and clump-deep, at the end of the experiment. There were so few plants in the other two treatments that they could not be meaningfully evaluated for plant growth. Most of the plant length in all cases was comprised of root; shoot lengths ranged from only 1.5 to 3.5 cm, with a few isolated exceptions.

As expected, the singulated plants were longer than the clumped plants (significant at P = 0.05) although the 3.8 cm difference in overall averages is not great, it does point out that competition was hindering growth of the clumped plants. Possibly, as solution, the seeding rate per clump could be reduced or else some thinning attempted after establishment is fairly secure. Early fertilization might also help.

There was no significant difference in plant length due to water level (Table 1) when averaged over all treatments. However, there was a trend for the clump-deep plants to be longer on the drier soil This suggests that the plants were overwatered following emergence. More research is needed on irrigation scheduling during the guayule establishment phase.

Plant Weight

Table 4 shows the average plant weights of the plants extracted from the length determinations. Plants from the driest treatments weighted

approximately twice as much as those from the wettest. Also, as in the length determinations, the singulated-deep plants weighed significantly more than the clump-deep plants (0.01 level). These weights roughly correspond to the length values, except that the weights are even more definitive. Hence, explanations for the two measurements are the same.

Plant Spacing

Table 5 shows the average plant spacings for the singulated-deep and clump-deep treatments. The other two treatments had too few plants to meaningfully analyze. The spacing data coincides with what would be expected from the stand data, i.e., average spacing between plants and clumps increases from the wettest to driest rows.

This table suggests that, under the conditions of this experiment, clumping was not particularly beneficial. The stands on the singulated-deep planting was much better than anticipated. The actual spacing between plants on the singulated-deep treatment was less than that between clumps for each water level. Even when one compares the spacings on a theoretical basis, taking account of maximum possible germination, the singulated-deep treatment looks good: 1.4 vs. 1.1 for the wettest treatment, and 2.2 vs. 1.8 for the medium treatment. Only for the driest treatment does one see much benefit from the clumping: 5.6 vs. 2.3.

However, these results do show that as planting conditions deteriorate then clumping becomes more beneficial. It was just that in this study, the emerging guayule seedlings experienced little difficulty traversing through the 5 mm of wet sand. Only when the soil was too dry for good germination and emergence (row 3) did the clumping significantly improve the theoretical stand.

Relatively low error terms also point out that in this study, on these two treatments which were successful, the plants were fairly uniformly distributed at the end of the establishment phase. This has been a problem in field studies, where even reasonable stands belie the fact that most surviving plants commonly are grouped in isolated patches where the soil conditions were just right.

Other Factors

Penetrometer data were taken at the close of the experiment to determine if surface crusts had formed in this sand. The procedure was to take 10 probes (Force Dial Dynamometer by Weight and Test Systems, Inc., Greenwich, CT) on each row for each replication; i.e., 30 readings per replication. It was anticipated that, if a crust existed, the row farthest from the drip line would have the strongest crust, commensurate with increased salt accumulation.

All readings gave strong evidence of crusting, but results for differences by row were inconclusive in that some readings from each row exceeded the limit of the instrument (5 kg). Hence, even through it was

not possible to relate crust strength to row and salt content, it was evident that strong surface crusts had formed in this sandy soil upon drying.

Crusting probably did not effect seedling emergence on the rows 3 and 13 cm distant from the drip line because they were continually wet during that phase, but crusting could have influenced emergence in the 23 cm distant row. Crusting will have to be monitored more closely in future establishment studies.

Fertilizer was applied twice to reps 2 and 4, but since it was applied rather late in the experiment and then to only 2 reps, results were inconclusive. Research on use of phosphorous to substitute for lack of mycorrhiza on soils foreign to guayule is particularly needed.

Soil temperature reading taken the first week while the plants were germinating and emerging showed that the dry soil surface (1 mm) reached 44 C, while the moist soil surface was 30 and 32 C at rows 3 and 23 cm from the drip line, and slightly hotter (2 C) 5 mm deep. These limited data suggest that the poor germination of the surface planted seeds was not the result of too high temperatures. However, better data are needed to clarify this. In general, more data is needed on how temperature extremes affect guayule germination/emergence under field conditions. Temperature undoubtedly affects optimum planting depth, planting rate, irrigation scheduling, and length of planting season.

SUMMARY AND CONCLUSIONS

One of the obstacles preventing the commercialization of guayule and other small-seeded new crops is the difficulty encountered in getting good stands with direct seeding. The purpose of this direct-seeding field experiment was to determine if guayule preferred surface or deep (5 mm) planting, preferred singulated or clumped seed placement, and to evaluate these 4 planting treatments as a function of 3 soil water levels. The water levels were obtained by planting rows 3, 13, and 23 cm distance from and parallel to a drip irrigation line. During the germination/emergence phase the irrigation system was run 6 hrs. per day. This was cut back during the subsequent establishment phase. The site was a plastic-lined 24 by 2.5 m sand pit. Conditioned guayule (cv. 11591) was planted September 11, 1986; i.e., during the Phoenix summer monsoon season.

Results showed that in the sandy soil used in the study, conditioned guayule (cv. 11591) completed the germination/emergence phase in less than one week from the two deep planting treatments, providing the water tension was kept low (rows nearest drip line). Practically no plants developed from the surface plantings irregardless of the soil water tension. Ninety percent of the deep planted clumps on the wettest soil treatment had one or more plants at the close of the 6-week establishment phase. The driest of the three water levels had 60% of the clumps with one or more plants after 6 weeks. The deep planted singulated treatment had a closer spacing of plants at the close of the experiment

than did the clumping treatment because the singulated seeds were planted closer together (2 cm on average vs. 10 cm, respectively), and because of the high emergence of all the deep seeded plants. Germinating/emerging guayule were shown to be extremely sensitive to soil moisture, but were shown to be damaged by too much water after emergence. Granulated Spectracide was found to provide an effective control against insects during the establishment stage.

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APPENDIX A -- Germination test of cv. 11591.

Both conditioned and unconditioned guayule cv. 11591 were tested for germination even though only conditioned seed was used in the field planting. Four replications of 100 seeds each were placed in petri dishes on wetted blotter paper, and the dishes sealed in clear plastic bags kept at 100% relative humidity. Seeds were germinated at 25 C under continuous light. Germination readings were taken on days 3, 5,7, 10, and 14. Seeds were considered to be germinated when the extended root and/or shoot was as long as the seed.

Results (Table 6) show that, as expected, the conditioned seed got off to a fast start and was essentially finished germinating in 6 or 7 days, while the unconditioned seed was slow starting and germination lagged on for two weeks. Unconditioned and conditioned seed ultimately attained the same total germination: 76 $\pm$ 6 and 78 $\pm$ 3 percent, respectively, and essentially the same acceptable germination: 67 $\pm$ 3 and 72 $\pm$ 6 percent, respectively.

The inferences of these germination findings are that (1) under irrigated conditions where the seed bed is kept continuously moist to promote germination and prevent soil-surface crusting, the rapidly emerging conditioned seed should save both water and the labor of putting it on, and provide a uniform stand amendable to early fertilization, pest control, and other beneficial agronomic practices; whereas, (2) under dryland farming the situation is rather indefinite. If conditions remain favorable throughout the germination, emergence, and early establishment phases, then the conditioned seed should be best. However, if favorable conditions are so ephemeral that the seeds only germinate but cannot be sustained, then probably a protracted germination period may be beneficial (Frasier, et al., 1987); which implies raw unconditioned seed or possibly a mixture of conditioned and unconditioned seed.

APPENDIX B. Pests.

Weeds were not much of a problem. Prior to planting, the plot had been rototilled and watered several times to sprout weed seeds near the surface. Several rakings dispatched them handily.

Animal pests, however, were a real problem throughout the experiment. Netting was placed over the entire plot immediately after planting to keep the hordes of birds from eating the seeds and newly emerging plants. Rodents had to be controlled periodically with bait.

Ants moved in the night after planting and quickly harvested replication 3 of all the surface-placed seeds and seemingly many of those planted 5 mm deep. The two surface treatments of that replication were replanted the next day, but no attempt was made to replant the 5 mm-deep plantings. The ants were controlled with Diazinone.

By day 4, other insects were discovered eating off the newly emerged seedlings. The plot was ringed with Spectracide to try keep the insects

out. Insects, however, continued to be a problem. The plot was sprayed with Malathion on days 5, 8, 15, and 18, but it was ineffective. On day 22 the plot was sprayed with Ortheen. It too was ineffective. Stand counts began to drop rapidly. On day 24, upon the recommendation of George Able (Amerind Agrotech Laboratories, Sacaton, AZ), Spectracide granules were spread over the entire plot. This treatment finally controlled the insect problem. The plot was retreated with Spectracide on day 32 after a heavy rain had washed the previously applied granules off the plot. The guayule stand remained fairly stable after the broadcast Spectracide treatment (Figs. 7 and 8).

Spectracide was the most effective of the three insecticides tried. Had it been broadcast at planting time, practically all the insect problems encountered and probably most of the early loss of stand undoubtedly would have been eliminated. This too needs confirmation.

PERSONNEL

D. H. Fink

Table 1. Summary of statistical significance of mean square values from analyses of variance.

		MEAN SQUARES[1/]					
		STAND				PLANT LENGTH	PLANT WEIGHT
		BY PLANTS		BY CLUMPS			
Source	DF	Day 7	Day 43	Day 7	Day 43	Day 43	Day 43
BLOCKS	3	103	55	253	261	12	.54E - 4
W	2	1694**	805**	2916**	1786**	90^{ns}	.84E - 4^{ns}
ERROR 1	6	45	29	85	81	24	.17E - 4
T	3	4050**	3051**	12870**	12370**	1223**	.61E - 3**
W x T	6	589**	257**	625**	370*	81**	.86E - 4**
RESIDUAL	27	41	27	105	106	15	.23E - 4

1/ W = water levels; T = treatments; * and ** represent significant difference at P = 0.05 and 0.01 levels, respectively; ns = not significant.

Table 2. Final guayule stand as function of seeding rate and expected germination.

	ROW DISTANCE FROM DRIP LINE (cm)		
	3	13	23
	- - - - - - - - - - - - - % - - - - - - - - - - - - -		
SINGULATED,	49 ± 13	34 ± 3	16 ± 6
5 mm Deep	(68)[1/]	(47)	(22)
	[-11][2/]	[-28]	[+129]
CLUMPED,	30 ± 6	19 ± 9	10 ± 6
(individuals)	(42)	(26)	(14)
5 mm DEEP	[-30]	[-37]	[-23]
CLUMPS,	90 ± 14	65 ± 21	51 ± 21
5 mm DEEP	[-4]	[-10]	[+2]

1/ Numbers in parentheses are germination percentages based on laboratory determined germination of 72%.

2/ Bracketed numbers are losses [-] or gaines [+] in plants or clumps on day 43 compared to day 7.

Table 3. Average plant length (root + shoot).1/

WATER2/ LEVEL	SINGULATED-DEEP	CLUMP-DEEP
	- - - - - - - - cm	- - - - - - - -
1	22.0 ± 1.4	16.8 ± 2.5
2	20.7 ± 5.1	17.1 ± 1.7
3	22.6 ± 6.1	20.0 ± 1.5
Avg.	21.8 ± 1.0	18.0 ± 1.8

1/ End of study. Average, where possible, of 10 or more plants per treatment/replication. The two surface planted treatments had too few plants to evaluate.

2/ 1, 2, and 3 represent rows spaced 3, 13, and 23 cm from drip line.

Table 4. Average plant weight (root + shoot)1/

WATER2/ LEVEL	SINGULATED-DEEP	CLUMP-DEEP
	- - - - - - - g x 10^3	- - - - - - -
1	11.9 ± 2.6	7.1 ± 1.2
2	12.5 ± 4.6	8.0 ± 1.8
3	22.8 ± 15.1	14.9 ± 2.6
Avg.	16.1 ± 6.7	10.0 ± 4.3

1/ End of study. Average, where possible, of 10 or more plants per treatment/replication. The two surface planted treatments had too few plants to evaluate.

2/ 1, 2, and 3 represent rows spaced 3, 13, and 23 cm from drip line.

Table 5. Average plant or clump spacing.1/

WATER2/ LEVEL	SING.-DEEP Avg. Spacing	SING.-DEEP Avg./theoret.4/	CLUMP-DEEP Avg. Spacing	CLUMP-DEEP Avg./theoret.4/
	cm		cm	
1	3.8 ± 0.8	1.4	11.4 ± 2.4	1.1
2	5.9 ± 0.6	2.2	17.0 ± 9.4	1.8
3	15.6 ± 6.1	5.6	23.3 ± 14.7	2.3
Avg.	8.4 ± 6.3		17.5 ± 6.0	
Theoretical3/ Spacing	2.8		10	

1/ End of study. Distance to first plant ignored.

2/ 1, 2, and 3 represent rows spaced 3, 13, and 23 cm from drip line.

3/ 200 cm/100 seeds/0.72 germination. Assumes perfect seed distribution when seeded.

4/ Measured average spacing ÷ theoretical.

Table 6. Germination of conditioned and unconditioned guayule cv. 11591.

Days	Germination1/ Total Cond.	Total Uncond.	Acceptable Cond.	Acceptable Uncond.
	%			
3	45 ± 8	8 ± 6		
5	66 ± 5	31 ± 9		
7	76 ± 3	54 ± 7		
10	78 ± 3	67 ± 6		
14	78 ± 3	76 ± 6	72 ± 6	67 ± 3

1/ 25 C; continuous light; 100% relative humidity.

GUAYULE - SAND PIT

T_1: Singulation; Surface (100 seeds, randomly spaced)
T_2: Singulation; 5 mm (ditto)
T_3: Clump; Surface (200 seeds; 10/clump, 10 cm apart)
T_4: Clump; 5 mm (ditto)

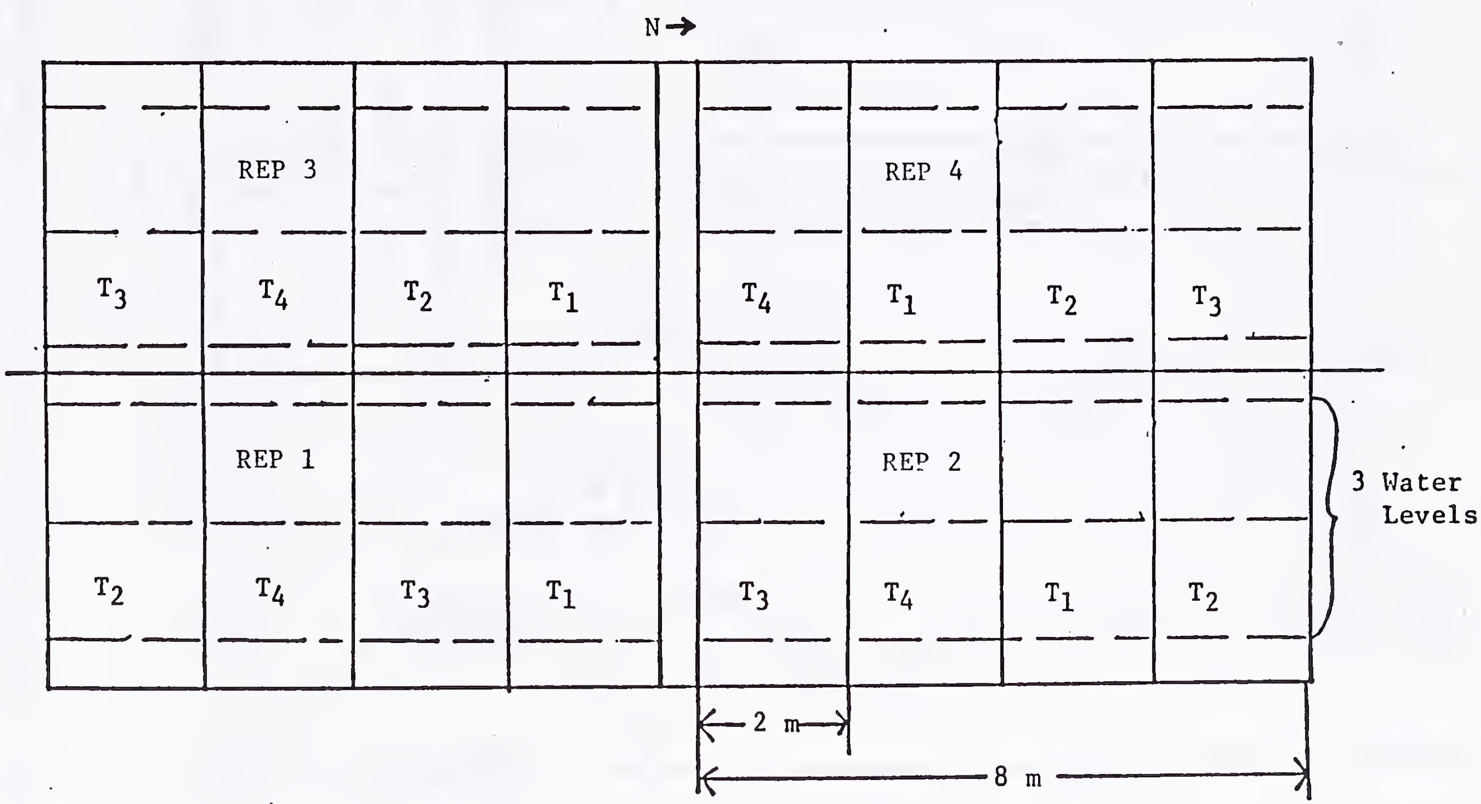

Figure 1. Experimental design.

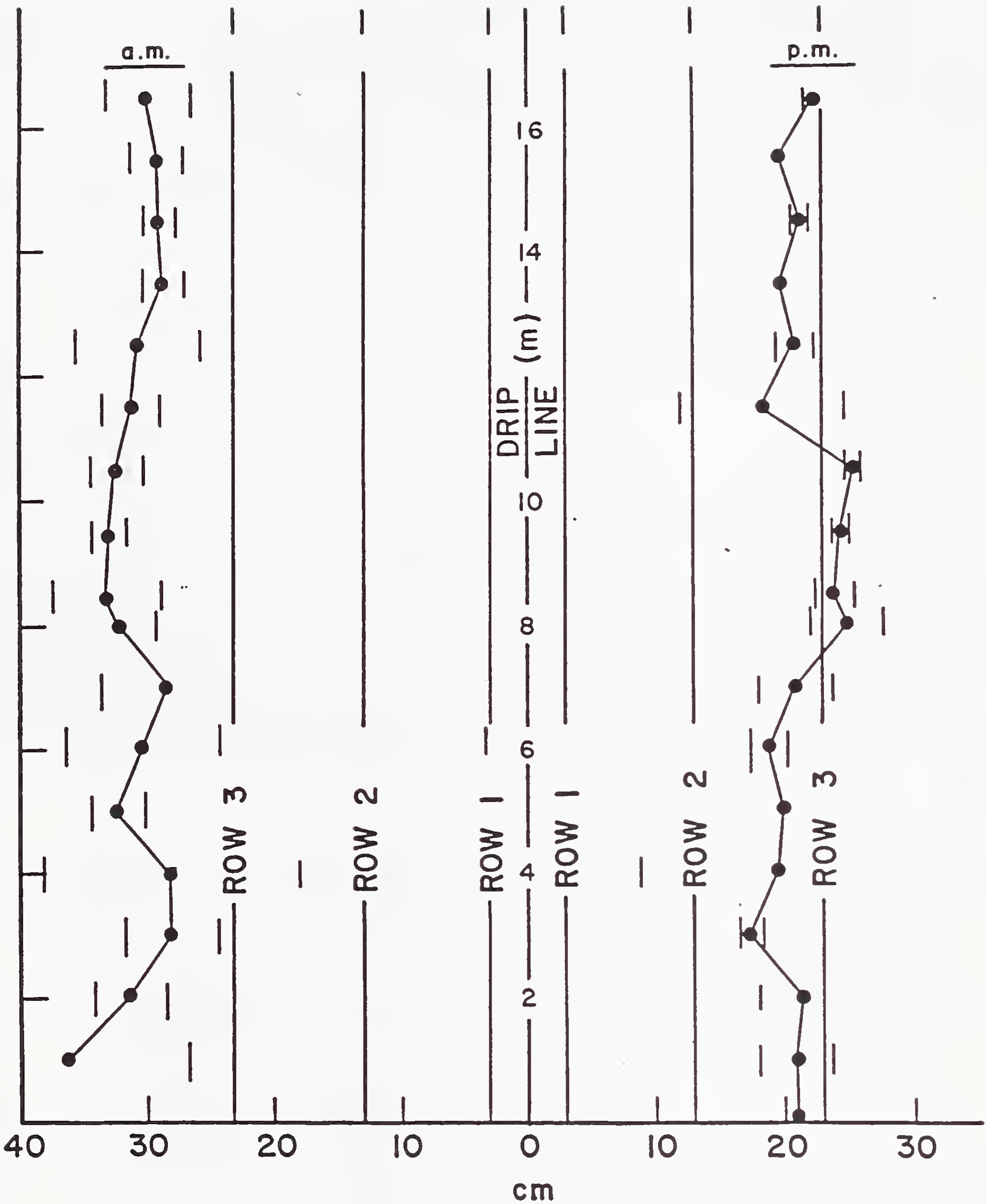

Figure 2. Water movement lateral to drip line as determined by limit of visual wetting front in early morning and late afternoon.

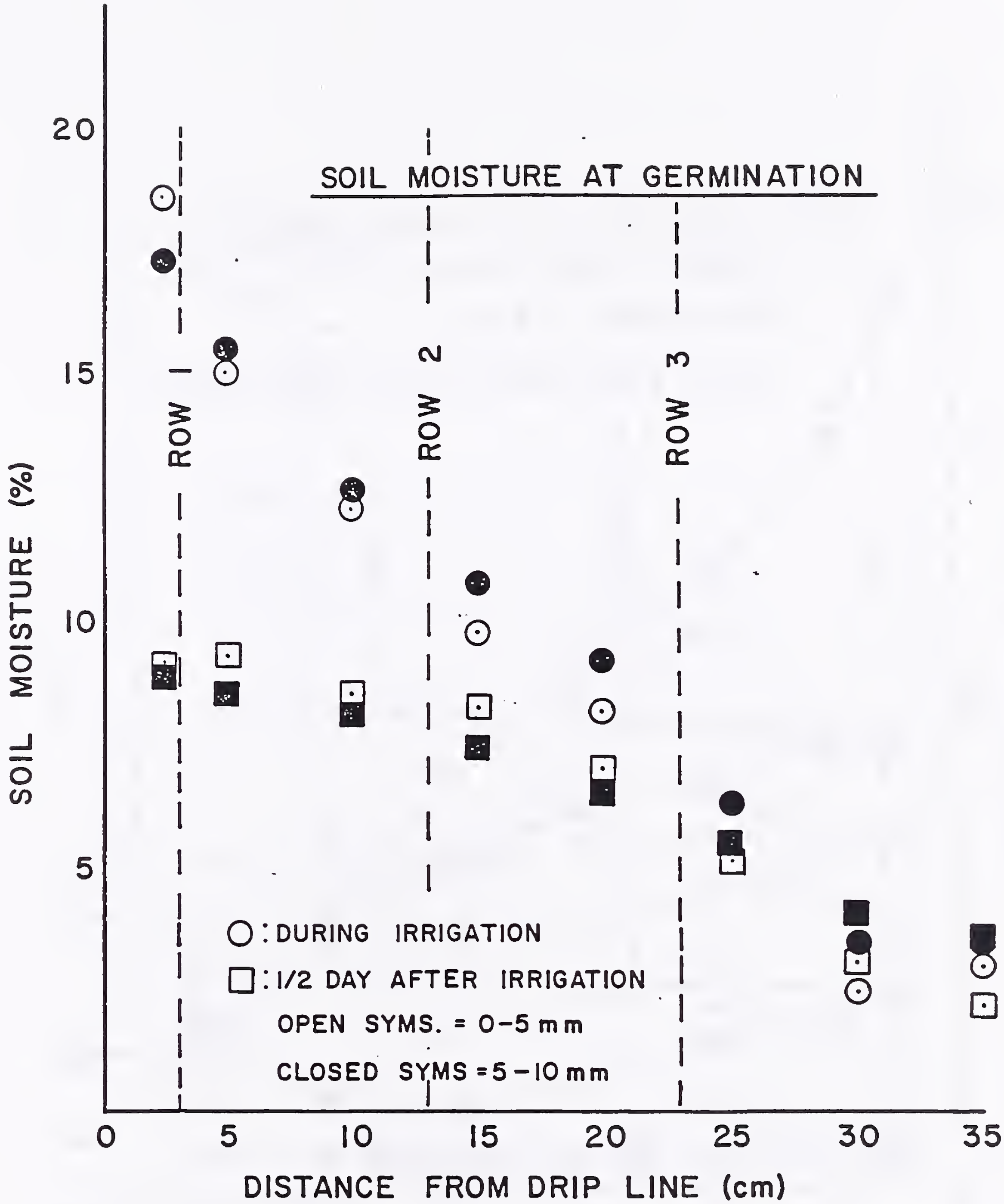

Figure 3. Soil moisture during the germination/emergence stage at 0-5 and 5-10 mm depths.

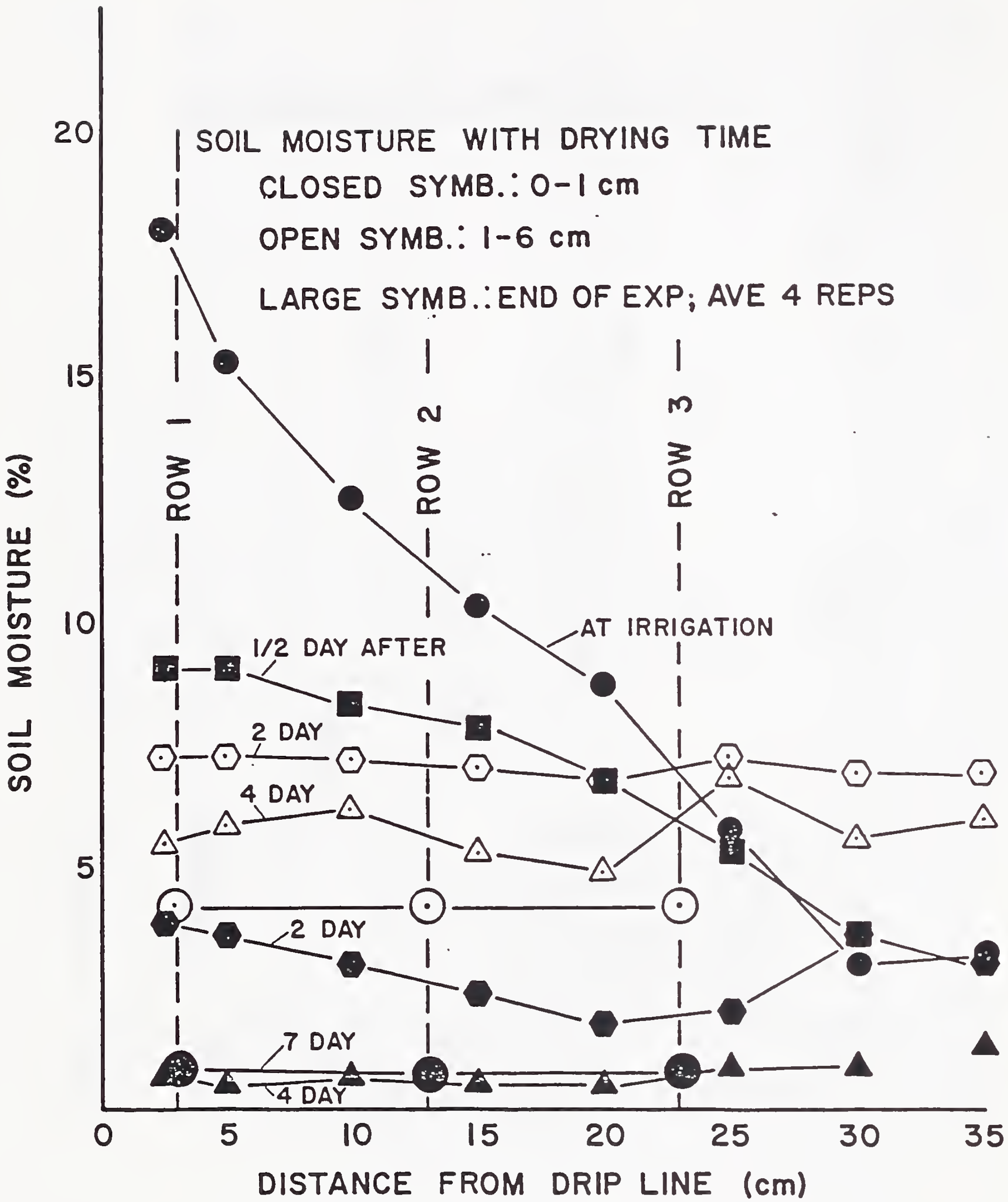

Figure 4. Soil moisture during the establishment stage at 0-1 and 1-6 cm depths.

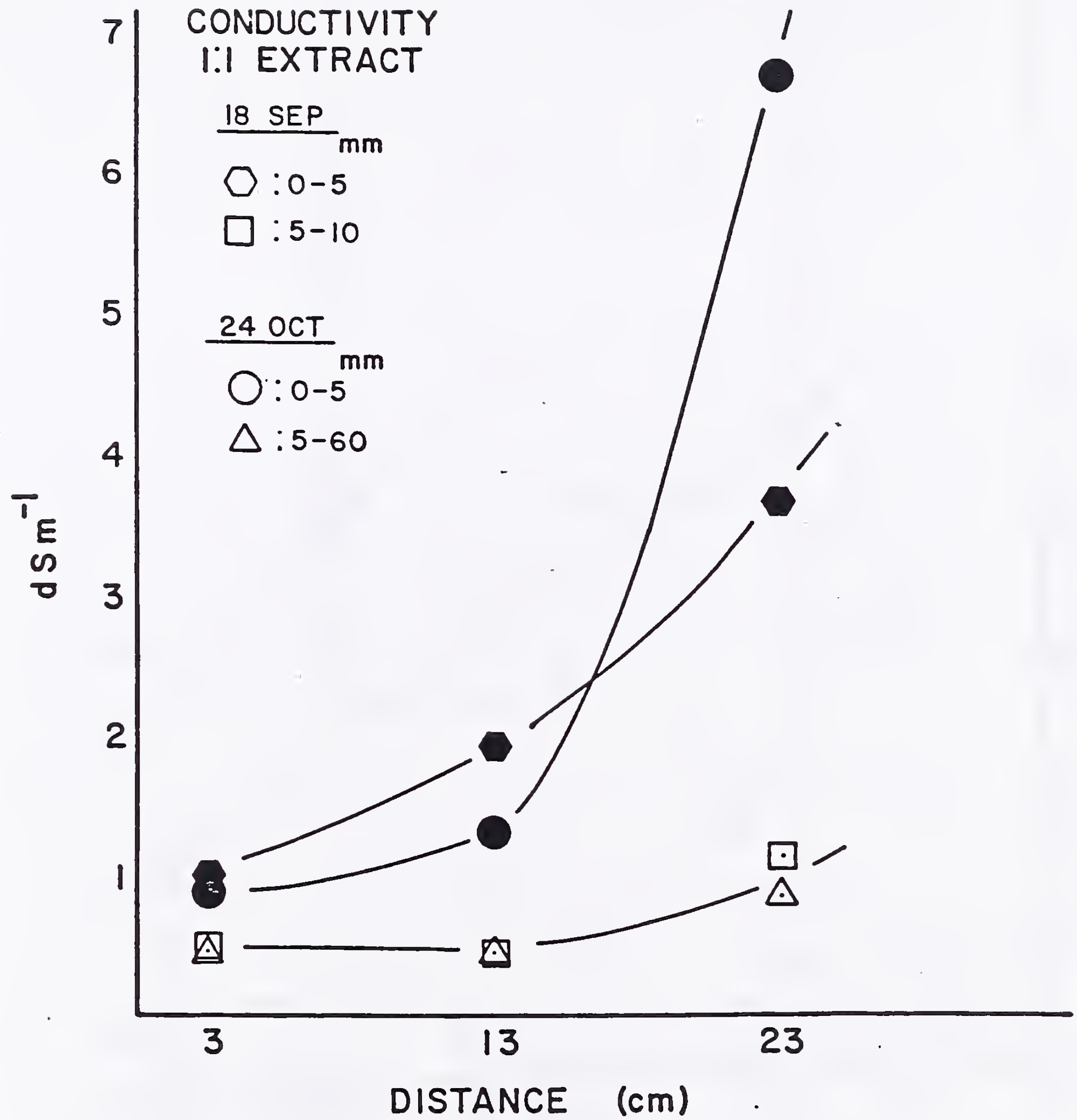

Figure 5. Salt content (conductivity) of 1:1 soil extracts at the end of the emergence stage and at close of the experiment.

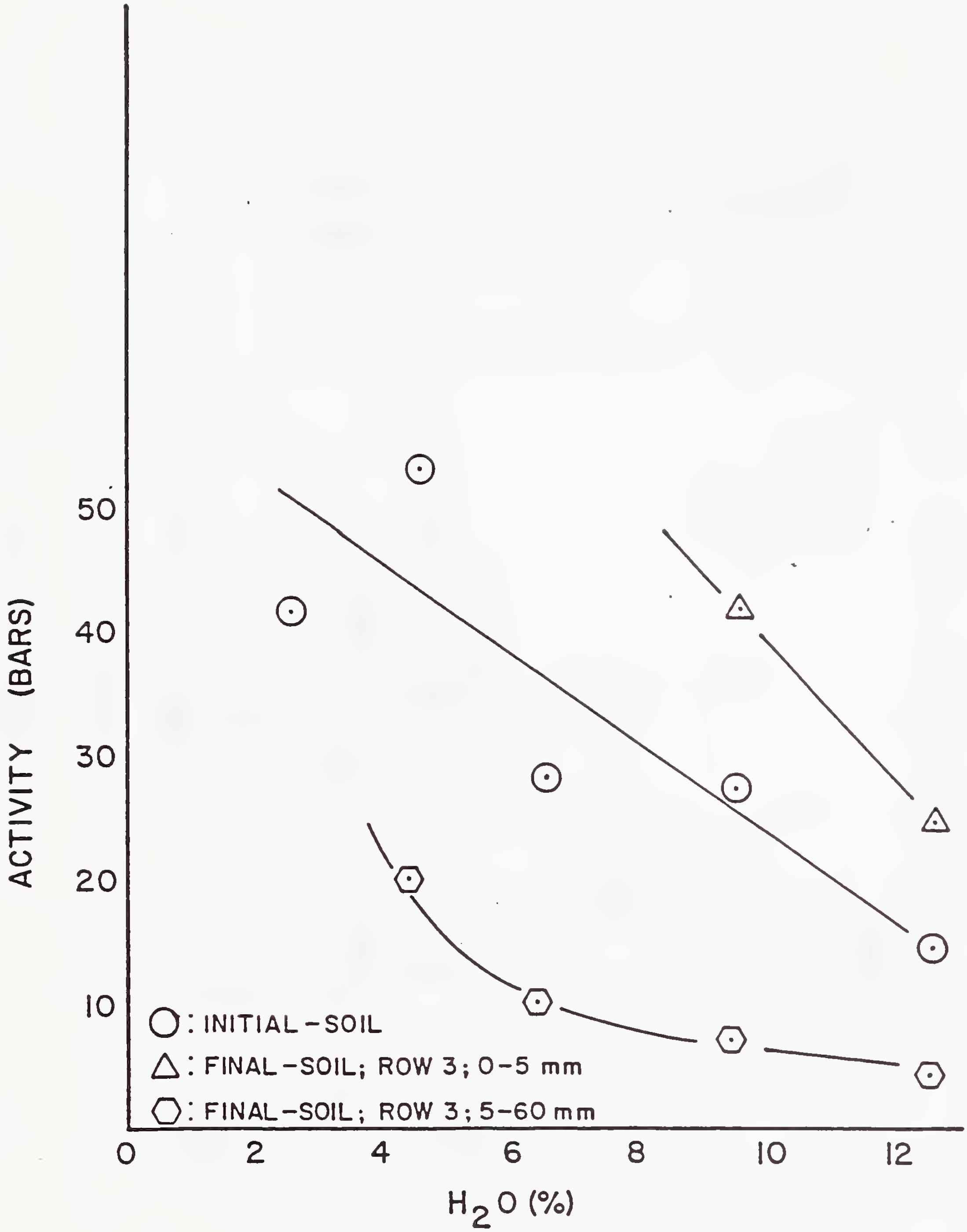

Figure 6. Water activity of soil taken from row 3 at close of experiment as a function of water content.

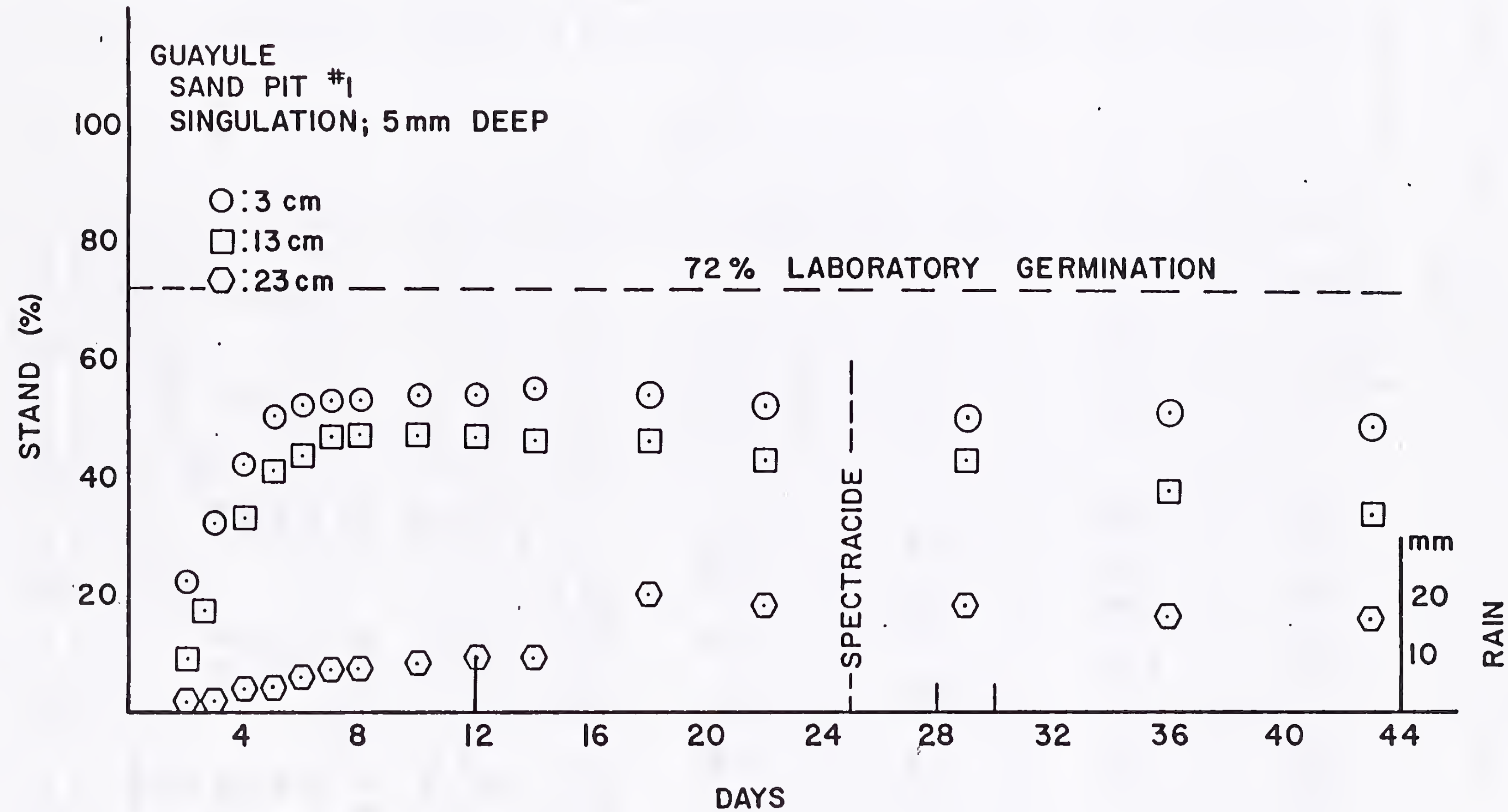

Figure 7. Emergence and stand of singulated--5 mm deep planted guayule over 6-week period.

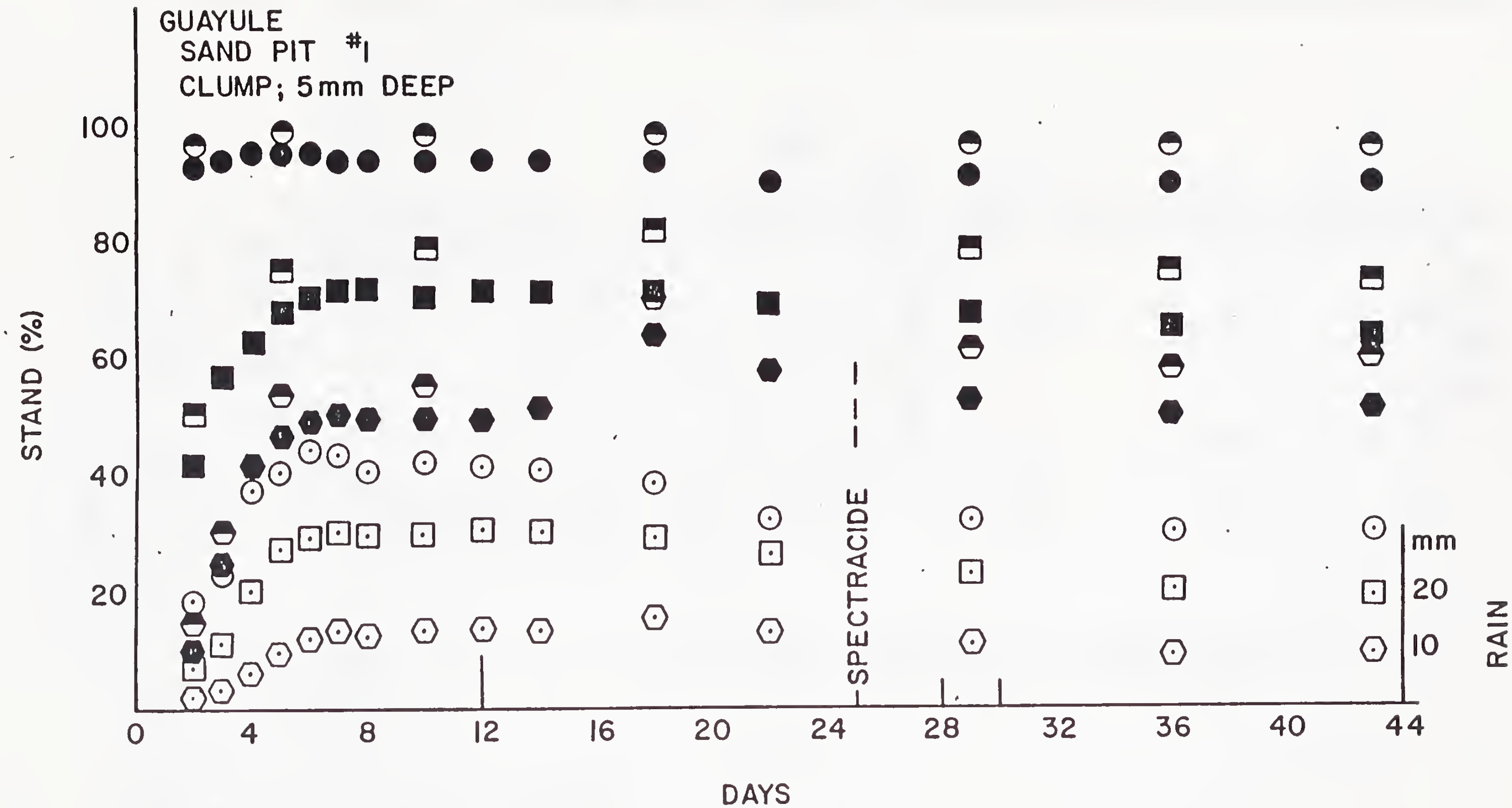

Figure 8. Emergence and stand of clumped--5 mm deep planted guayule over 6-week period, showing individual plant counts (open symbols) and clump counts (closed).

TITLE: BIOREGULATION OF RUBBER AND RESIN PRODUCTION IN GUAYULE

STRATEGIC PLAN: 2.3.04.1.p CRIS WORK UNIT: 5422-20740-012

INTRODUCTION

During the last several years we have been testing the effects of the bioregulator DCPTA on rubber production of guayule (Parthenium argentatum Gray), a xerophytic shrub adapted to the desert southwest (Ray, 1983). Although other researchers have reported success in stimulating terpenoid synthesis in citrus (Yokoyama et al., 1977b) and rubber synthesis in guayule (Yokoyama et al., 1977a; Benedict et al., 1983; Hayman et al., 1983) we have had little success in promoting increased guayule rubber yields using DCPTA under field conditions at this laboratory (Bucks et al., 1984: Allen et al., 1986).

During 1986 we tried two different approaches to bioregulation of rubber production. The first approach involved the application of DCPTA to other Parthenium species, that are closely related to guayule, which are prolific biomass producers but which produce smaller quantities of rubber than guayule. This approach is based on the assumption that guayule may not respond to DCPTA application in the field due to genetic and physiological limitations to further rubber accumulation, whereas the other Parthenium species may have greater capacity to store additional rubber molecules. The other reason for including the other Parthenium species in this years field study is that they are currently being used to produce hybrids with guayule that are capable of increased biomass production. One of these hybrids, cv. Arizona 101, has been included in this years field test.

The other approach to guayule rubber bioregulation is to determine the effect of deflowering on rubber and biomass yield. This approach is based on the assumption that photosynthate which is used for reproduction is diverted from biomass and rubber production. The final harvest and data analyses from these two experiments will be conducted in January and February of 1987. Therefore, the detailed materials and methods used in these studies will be reported in the 1987 Laboratory Annual Report.

In addition, this report contains the results from the 1985 field trial which tested time of year and frequency of DCPTA application on guayule rubber and resin yield (Allen et al., 1986).

MATERIALS AND METHODS

The 1985 Laboratory Annual Report (Allen et al., 1986) describes in detail the experimental design and procedures used to test the time of year and frequency of DCPTA application on guayule rubber production. In brief, cv. N565 II plants were transplanted into the field in a randomized complete block experimental design at the University of Arizona Maricopa Agricultural Center on 15 November 1984. They were immediately irrigated and again as necessary during the rest of the experiment to avoid stress conditions.

Applications of 5000 ppm DCPTA were made according to the schedule in Table 1 such that at each application the adaxial leaf surfaces of the plants were completely covered with the solution. Tween 80 was included in the solution as a wetting agent.

Four plants from each plot were randomly selected for harvest on February 19, 1986. The plants were returned to the laboratory where fresh weights were immediately measured. The plants were air dried in a greenhouse at approximately 25 to 35 C for one month before a section of the main plant axes that included approximately 20 cm of root and 20 cm of stem material were ground through a 2 mm screen. The ground samples were analyzed for rubber and resin content according to the gravimetric procedure described by Black *et al.* (1983). Fresh weight, and percent rubber and resin data were analyzed using analyses of variance and orthogonal comparisons of treatment means.

RESULTS AND DISCUSSION

The analyses of variance showed that there were no statistically significant treatment effects on fresh weight, percent rubber or percent resin (Table 2). Orthogonal comparisons of treatment means further indicated that neither the timing of the DCPTA applications or the total number of applications produced any significant effect on fresh weight, or percent rubber and resin. The treatment means are shown in Table 3, and, again, show no apparent trend in the results with respect to DCPTA effects, even though other studies have indicated that the same concentration of DCPTA used in this study (5000 ppm) has increased rubber content of greenhouse- and field-grown guayule by two- to three-fold (Yokoyama *et al.*, 1977a; Benedict *et al.*, 1983).

CONCLUSION

After several years of testing it appears that the use of the bioregulator DCPTA is not economically feasible for field use in promoting guayule rubber yields in Arizona. This conclusion is based on the results of extensive field and greenhouse studies that have investigated the effects of DCPTA application date, concentration, and frequency of application. In none of our studies have we found statistically significant increases in rubber production associated with the application of DCPTA.

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PERSONNEL

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Table 1. Frequency and timing of DCPTA applications to guayule during 1985 field experiment.

Treatment Number	Application Date - 1985				Total Number of Applications
	May 6	July 11	Sept 13	Dec 12	
1	X				1
2		X			1
3			X		1
4				X	1
5	X	X	X	X	4
6 (control)					0

Table 2. Summary of statistical signifiance from analyses of variance for fresh weight, percent rubber, and percent resin from 1985 field trial of DCPTA effect on guayule.

Source	d.f.	Mean Square		
		Fresh Weight	Percent Rubber	Percent Resin
Total	23			
Blocks	2	11203 ns	0.007 ns	0.99 *
Treatments	7	7960 ns	0.200 ns	0.42 ns
Error	14	4773	0.212	0.25
C.V.		896.41	3.93	3.53

* Significant at 0.05 level.
ns not significant.

Table 3. Treatment means for fresh weight, percent, rubber and percent resin from 1985 field trial of DCPTA effect on guayule.

Treatment Number	Mean		
	Fresh Weight (g)	Percent Rubber	Percent Resin
1	502	5.5	7.4
2	459	5.2	7.0
3	622	5.2	7.0
4	545	5.5	7.5
5	561	5.1	7.5
6 (ck)	529	5.9	6.4

TITLE: DIRECT SEEDING FOR ECONOMICAL GUAYULE RUBBER PRODUCTION

STRATEGIC PLAN: 1.3.03.1.d 80% 2.3.04.1.n 20% CRIS WORK UNIT: 5422-20740-012

INTRODUCTION

Commercial production of guayule (Parthenium argentatum Gray) has been hindered by expensive or inappropriate agronomic practices, particularly the techniques associated with stand establishment. Guayule is presently being established through the transplanting of greenhouse-grown seedlings into the field. The cost of this establishment including greenhouse and transplanting practices was estimated in 1985 to be from $900 to $1200/ha, and the development of direct seeding techniques could reduce this in half. Unfortunately, earlier field experiences with guayule direct seeding have been marginally successful, suggesting that direct seeding would be feasible only under certain management or environmental conditions.

We have shown in previous field and laboratory tests that planting quality has been improved by conditioning guayule seeds with polyethylene glycol (PEG), gibberellic acid (GA), and light. In brief, guayule seed conditioning enhances both germination and the development of normal seedlings over a broader temperature range (Chandra et al. 1986b) Field studies conducted at Yuma, Arizona, on a sandy soil in the Fall 1983, Spring 1984 and 1985, and Fall 1984 and 1985 indicated that germination (emergence rates) were increased by using fluid drilling to plant guayule seeds and that precise sprinkler irrigations were required for plant survival (survival rates). In terms of planting rates, at least 40 seeds/m (12 seeds/ft) were required to obtain moderate plant populations when the guayule seeds had an initial germination rate of better than 60%. Although satisfactory stands were achieved in three out of five experiments with conditioned seeds, guayule seedling vigor and salt tolerance were possibly the two main problems to be solved before direct seeding could be recommended as the preferred establishment practice for this crop (Bucks et al. 1986).

In 1986, Summer and Fall direct seeding experiments were conducted at the Maricopa Agricultural Center, University of Arizona, Maricopa, Arizona, on a Casa Grande sandy loam soil. The overall objective of these studies was to improve field planting and water management for obtaining reliable and economical direct seeding of guayule. Nursery cover crops and synthetic shade covers were investigated for the first time in terms of increasing both guayule seedling emergence and survival.

Field Procedures

Summer 1986

The field, which was 13 m (twelve beds) wide and 183 m long, was divided into three replications of two irrigation treatments (wet and dry) as main plots, two row cover treatments (no cover and a wheat cover crop)

as subplots, and two seed treatments as sub-subplots (conditioned and nonconditioned cv. 11591 seeds). Observational row covers of cheese cloth (30% shade), polyshade cloth (40% shade), straw (13 mm thick), and etc. were placed on the buffer rows (see Figure 1). The wheat shade crop was planted on the outside edge of the beds in six subplots that were four beds wide and 46 m long, at a rate of 92 seeds/m on April 20. Conditioned and nonconditioned seeds were planted on June 11 at a rate of 46 seeds/m when the wheat was about 200 mm in height. The seeds were planted into a small corrugation (20 mm deep) constructed in the center of each bed for all the treatments. The conditioned seeds were treated by the Plant Molecular Genetics Laboratory, Beltsville, Maryland, using 25% polyethylene glycol (PEG, MW 8000, an osmoticum to prevent water uptake injury), 0.2% Thiram fungicide adjusted to pH 8 with a saturated solution of $Ca(OH)_2$, 0.5 mg/ml KNO_3 (an oxidant), and 10^{-4} m gibberellic acid (GA, a growth hormone enhancing elongation) under a continuous light treatment for three to four days (Chandra et al. 1986b). The Thiram fungicide has been shown in the laboratory to reduce fungal disease problems and not lower germination rates (Chandra et al. 1986a). The conditioned seeds had a maximum laboratory germination rate of 61%, while the nonconditioned had a rate of 46%.

Irrigation water was applied immediately after seeding using a solid-set sprinkler system equipped with 3.2 mm inside diameter nozzles spaced every 9 m along the pipeline. The irrigation schedule was daily for the first four days, followed by every three days for the next ten days, and then every three to five days on the wet treatment versus every six to seven days on the dry treatment for the remainder of the two-month trial. If precipitation occurred, irrigations were delayed. There was no nitrogen fertilizer applied as the seedlings emerged. Data collected included irrigation water applied, precipitation, hourly air and soil temperatures, seedling counts, and seedling growth.

Fall 1986

Based on results from the Summer 1986, a second experiment was initiated in the Fall 1986 on the same field using a split plot design with seven row cover treatments and two seed treatments as subplots. The main plots were 14 m wide and 2 m long; and each subplot was 3 m (three beds) wide and 2 m long, which was replicated four times across the main plots. The row covers were as follows (A) no cover, (B) sorghum cover crop, (C) Agronet (10% shade, solid cover), (D) Reemay (5% shade, solid cover), (E) polyshade cloth (40% shade, solid cover), (F) polyshade cloth strips (40% shade, 300 mm wide strips), (G) American straw mat (25 mm thick, solid cover); and (H) straw (13 mm thick, solid cover). The sorghum crop was planted as two outside edge rows/bed (about 300 mm from the proposed guayule seed row) on August 22 at 13 seeds/m and trimmed back to a 300 mm height just prior to seeding guayule. The seed treatments were cv. 11591 conditioned (72% maximum laboratory germination rate, treated in the same manner used in Summer 1986) and nonconditioned (67% maximum laboratory germination rate) seeds that were planted on September 30 again at 46 seeds/m using the same fluid drilling method used in the Summer 1986.

There was also a small duplication area where all the row cover treatments except for the sorghum crop were established in individual 3 m by 3 m plots. A meteorological station, equipped with a Campbell Scientific CR-21X Data Logger and Multiplexer, measured air and soil temperatures, net and solar radiation, and relative humidity. Then, in the main sorghum plot, a CR-21 Data Logger was set up to monitor soil temperatures, and below-canopy relative humidity and solar radiation. These hourly meteorological measurements were converted to daily totals and averages. Sprinkler irrigations, for the entire experiment, were scheduled daily for the first four days after planting, followed by irrigations on the sixth, ninth, and 13th day. Information was also recorded on seedling counts, soil salinity, soil water contents, and seedling growth. Soil water contents were taken prior to planting and seven and 25 days after planting. Plant samples were collected under the (C) Agronet, (D) Reemay, and (E) polyshade cloth on the 25th day after planting to evaluate plant heights and weights.

Results and Discussion

Summer 1986

The total irrigation water applied on the wet treatment was 109 mm compared with 83 mm on the dry treatment from June 11 to August 11, while the precipitation totaled 22 mm over the same period (Table 1) in the Summer 1986. Guayule seedling counts were made at 15 m distances on three replications for seven selected dates with no cover crop, a wheat cover crop, and several observational row covers. Table 1 presents guayule seedling counts for three selected dates; Figure 3 shows seedling counts for seven dates with a wheat cover and without a wheat cover crop, and Figure 4 shows seedling counts for seven dates for the observational polyshade and cheese cloth treatments. Guayule seed germination (initial emergence) was essentially complete on June 17, six days after planting. The first plant counts, taken three days later on June 20, indicated about the same number of seedlings existed prior to the initation of wet and dry irrigation treatments for both the no cover and wheat cover crop treatments (Table 2 and Figure 1). However, several weeks later on August 7, the drier irrigation treatment with nine irrigations compared to the wetter treatment with 13 irrigations had a 35% higher plant survival (3.4 versus 2.5 surviving seedlings/m). In terms of the row cover treatments, the wheat cover crop increased seedling emergence by 52% (9.0 versus 5.9 emerging seedlings/m for both irrigation treatments) over the no cover crop on June 20. After the typical seedling losses during the first- and second-leaf stages of growth, the wheat shade increased seedling survival four-fold compared with no shading (4.7 versus 1.1 surviving seedlings/m) by August 7. The shade crop not only improved seedling emergence but protected the seedlings from wind and physical damage. In terms of seed treatments, the conditioned seeds germinated at an average rate that was 9% greater than the nonconditioned seeds (7.8 versus 7.1 emerging seedlings/m for both irrigation and row cover treatments on June 20). At the end of the experiment, the plant survival was 17% higher for the conditioned compared with nonconditioned seeds (3.1 versus 2.7 surviving seedlings/m) on August 7. An optimal of final plant survival of between three to five plants/m was obtained with the combination of conditioned guayule

seeds and a wheat cover crop. Although the conditioning of the guayule seeds enabled the seeds to germinate sooner than the nonconditioned seeds (four rather than six days after planting), the higher soil temperature in the summer possibly reduced overall benefits of improved plant survival with the conditioned seeds.

Weekly air and soil temperatures with and without a wheat cover crop are shown in Table 1. The wheat shade maintained soil temperatures during the first week of germination that averaged 2.7° C lower maximums, 2.3° higher minimums, and 2.2° C cooler means at the 10 mm depth than without the cover crop. Over the entire two-month establishment period, soil temperatures at the 30 mm depth had nearly the same maximums, 1.2° C higher minimums, and 1.5° C cooler means for the shade crop versus no shade.

On the observational covers as shown in Figure 4, the cheese cloth shade increased the final plant survival by 75% over the most promising conditioned seeds and wheat cover crop treatment combination (8.9 versus 5.1 surviving seedling/m) on August 7, and the polyshade cloth increased the final plant survival by 122% over the same treatment combination (11.3 versus 5.1 surviving seedlings/m) on August 7. The straw cover treatment showed little promise since plant survival was only slightly improved over the no cover crop, possibly due to prolonged high soil water contents, reduced exposure to light (excessive shade), and increased environment for insects.

Fall 1986

The total irrigation water applied was 61 mm from September 30 to October 14 for the first two weeks after planting, and the precipitation totaled 14 mm (Table 3) in the Fall 1986. Average air temperatures were nearly the same for the bare soil condition (no cover crop) and the sorghum cover crop; however, daily solar radiation was 30% to 90% greater for the bare soil compared with the sorghum crop. The average decrease in solar radiation on the sorghum crop was 39% over the no cover treatment during first two weeks of seedling emergence.

Seedling germination began on October 6 and 7, seven to eight days after planting depending on the type of row cover treatment. Figure 5 and 6 show that the polyshade cloth had the greatest emergence and survival of guayule plants by a wide margin over the other shade covers for both conditioned and nonconditioned seeds. In all cases, the seven row cover treatments did increase initial germination or emergence rate over the no cover crop check, such that the order from the highest to lowest number of emerging seedlings 10 days after planting were as follows: (E) polyshade cloth, (C) Agronet, (F) polyshade strips, (D) Reemay, (G) American straw mat, (B) sorghum crop, (H) straw, and (A) no cover. A major attack by flea beatles (Systena blanda), from the nearby cotton fields being harvested, began on about October 13 and significantly reduced plant survival on all treatments. There was not enough time to eradicate the insects; however, differences in emergence survival rates can be explained for most of the row cover treatments during the first two weeks after planting. Seedling counts were lower on the (B) sorghum cover crop because the flea beatles appeared first on this treatment,

and the combination of insects and unhealthy plants from too much shading reduced seedling survival with the sorghum crop. The (F) polyshade strips had lower survival rates than the (E) polyshade cloth and (C) Agronet treatments, because the narrow strips were constantly wind blown leaving some of the seedling beds exposed to direct sunlight similar to the (A) no cover check. Although emergence was higher on (C) Agronet, the plant survival was lower on the (C) Agronet and (D) Reemay compared to the (E) polyshade strips, possibly because of the higher soil temperatures on these two white materials compared to the green polyshade strips. The (G) American straw mat and plain (H) straw provided almost complete shading, higher soil moisture contents, and a large population of crickets which reduced both seedling emergence and survival.

Soil water content measurements for the eight row cover treatments are shown in Figure 7. The highest initial soil water contents in the 0-10 mm soil depth on the (B) sorghum cover crop (G) American straw mat, and (H) straw alone resulted in the lowest initial seed germination or emergence rate. Better seedling emergence and survival occurred on the (E) polyshade cloth (C) Agronet (F) polyshade strips, and (D) Reemay row than the (B) sorghum cover crop and (H) straw cover treatments which resulted in the lowest initial germination one week after planting. Plant survival was also poor on the (G) American straw mat since high soil water contents were maintained up to the last counting date; conversely, on the (B) sorghum cover crop and (H) straw cover treatments, the soil dried out somewhat; and the plant survival was improved during the second week after the poor initial germination. The best seedling emergence and survival was obtained on the (E) polyshade cloth, (C) Agronet, (F) polyshade strips, and (D) Reemay row covers, where the soil water contents were maintained within the wet range for the first week followed by moderate drying during the second week after planting of the guayule seeds.

Daily soil temperatures on the eight row cover treatments are presented in Table 4. Generally, soil temperatures were not related directly to the plant germination or survival rates because of differences in soil water contents, wind movement, and possible incoming solar radiation. However, the most promising (E) polyshade cloth, (C) Agronet, and (D) Reemay row cover treatments that maintained more favorable soil temperatures prior to germination and during early seedling growth, also maintained fairly uniform soil water contents, elevated humidity near the seed row, and protected the seedlings from wind and blowing dust compared to the (A) no cover crop. The (E) polyshade cloth had average soil temperatures that were lower than the (C) Agronet and (D) Reemay treatments but nearly the same as the (A) no cover crop. The (E) polyshade cloth, which was green in color, offered effective shading and appeared to reduce the intensity of the sunlight; whereas the (C) Agronet and (D) Reemay covers, which were white in color, offered little shading and acted more as a collector for solar radiation. All three of these covers provided some protection from wind and insect damage.

Summary and Conclusions

Direct seeding of guayule for obtaining uniform plant stands has been a difficult task. To date, the best results have been obtained in the field when the seeds were conditoned with polyethylene glycol, gibberellic acid, and light; planted using fluid drilling techniques; and sprinkler irrigated over a two- to three-month period. In the summer and fall of 1986 in central Arizona, conditioned guayule seeds out performed the nonconditioned seeds in terms of seedling germination and survival. Water management observations also indicated that uniform soil water contents need to be maintained throughout initial seed germination; however, lower soil water contents or a drier irrigation treatment may enhance establishment during initial seedling development stages after emergence. A dramatic increase in plant survival ratios were obtained in the summer when the seedlings were shaded by wheat crop or synthetic material. Possible advantages of shading include maintaining more favorable soil temperatures for seedling germination and survival, maintaining more uniform soil water contents, elevating humidity near the seed row, and protecting seedlings from wind damage. Shading also improved emergence and initial seedling growth in the fall; however, an unfortunate insect attack reduced overall success in this later planting. The usage of a shade or cover crop would not only improve chances for the successful direct seeding of the perennial guayule crop by protecting the young seedling, but the nursery crop should decrease the cost of guayule establishment by providing some income from a short-term, annual crop. Guayule direct seeding studies will be expanded in 1987 with plantings at Yuma and Maricopa, Arizona. Emphasis will be placed on using barley and wheat shade crops, comparing imbibed (pregerminated) conditioned guayule seeds versus dried conditioned seeds, and planting guayule seeds at a shallow soil depth rather than on the soil surface.

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PERSONNEL

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Table 1. Weekly water applications, precipitation, air temperatures, and soil temperatures at 10 and 30 mm soil depths in the Summer 1986 at the Maricopa Agricultural Center, Maricopa, AZ

Dates	Water Applied (mm)		Precipitation (mm)	Air Temperatures °C			Soil Temperatures, °C																	
							No Cover						Mulch and Wheat Cover						Wheat Cover					
							10 m			30 m			10 mm			30 mm			10 mm			30 mm		
	Wet	Dry1/		Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
11 Jun-19 Jun	25.6	25.6	-	40.5	20.9	30.7	41.0	16.6	28.8	37.3	20.1	28.7	37.6	19.6	28.6	36.1	20.8	28.5	38.3	18.9	28.6	35.8	19.7	27.8
20 Jun-26 Jun	19.2	12.8	-	40.1	21.0	30.6	46.6	18.4	32.5	41.8	19.4	29.3	40.3	21.2	29.7	37.5	22.4	30.0	39.9	20.5	30.2	37.6	21.4	29.5
27 Jun-03 Jul	12.8	12.8	8.9	38.3	24.9	31.6	45.8	23.4	34.6	44.2	24.0	34.1	42.2	24.8	33.5	38.6	25.8	32.2	41.5	24.4	33.0	39.0	25.2	32.1
04 Jul-11 Jul	12.8	6.4	Trace	37.8	23.0	31.1	46.1	22.5	32.7	43.8	23.4	33.6	42.2	24.1	32.2	40.1	25.2	31.4	43.8	23.3	31.5	39.3	24.5	30.9
12 Jul-16 Jul	6.4	6.4	-	5 DAYS DATA MISSING																				
17 Jul-24 Jul	6.4	-	12.7	36.0	22.2	29.2	48.4	23.3	33.3	45.2	23.7	34.4	44.8	24.5	34.0	41.8	25.8	32.2	45.6	23.8	33.4	40.2	25.2	31.3
25 Jul-31 Jul	12.8	12.8	-	40.5	21.0	30.8	54.9	22.6	38.8	50.1	23.6	36.9	51.1	24.7	37.9	45.5	26.6	36.1	50.7	20.3	35.5	42.6	25.6	34.1
01 Aug-11 Aug	12.8	6.4	-	39.3	25.2	32.3	49.4	25.5	37.9	47.2	25.9	36.6	46.6	26.6	36.6	42.8	27.8	35.3	45.8	25.9	35.9	41.3	27.0	34.2
Total or Average	108.8	83.2	21.6	38.9	22.6	30.9	47.5	21.8	34.1	38.7	22.9	32.9	43.5	23.7	33.2	40.3	24.9	32.2	43.6	22.4	32.6	39.4	24.1	31.4

1/ Dry irrigation began on 20 June 1986, nine days after planting.

Table 2. Guayule seedling counts per a 15 m distance for three selected dates with no cover crop, a wheat cover crop, and several observational row covers at Maricopa Agricultural Center for cv. 11591 seeds planted on June 11, 1986.

Row cover treatment1/	Irrigation Treatment and Counting Date						
	Wet			Dry			Wet & Dry
	6/20	7/10	8/7	6/20	7/10	8/7	8/7
No cover crop							
Conditioned seed	91	12	9	101	44	27	18
Nonconditioned seed	86	19	13	79	29	18	16
Mean	88	16	11	90	37	23	17
Wheat cover crop							
Conditioned seed	137	88	70	139	101	82	76
Nonconditioned	127	74	59	136	88	73	66
Mean	132	81	64	137	94	78	71
Observational covers							
Cheese cloth	223	175	120	242	220	146	133
Polyshade cloth	224	170	136	274	254	202	169
Straw cover	58	37	23	103	67	41	32

1/ Mean of six counting plots (two counting distances times three replications) for no cover crop and wheat cover crop treatments, and two counting plots for the observational covers.

Table 3. Daily water applications, precipitation, air temperatures, relative humidity, solar radiation, and net radiation in the Fall 1986 at the Maricopa Agricultural Center.

Dates	Water Applied (mm)	Precipitation (mm)	Air Temperature[1] No Cover Max	Min	Avg	Sorghum Cover Max	Min	Avg	Relative Humidity, %[1] No Cover Max	Min	Avg	Total Solar Radiation[1] Joules/m²/day No Cover	Sorghum	Total Net Radiation[1] Joules/m²/day No Cover
30 Sep	10.7	-	31.7	10.5	21.4	-	-	-	87.6	14.2	44.4	-	-	-
01 Oct	10.7	-	26.4	13.6	21.0	-	-	-	69.1	22.7	43.8	19.3	-	12.6
02 Oct	5.3	-	26.1	12.3	18.3	26.9	13.2	20.3	92.9	37.5	66.2	23.8	18.0	17.5
03 Oct	6.6	2.5	30.6	9.4	19.8	27.8	12.7	18.7	91.2	34.1	62.1	-	15.4	-
04 Oct	-	-	27.5	13.4	20.2	30.8	10.5	19.8	87.0	40.3	63.8	20.8	15.5	15.3
05 Oct	11.2	-	32.0	12.3	21.5	27.4	13.8	17.9	91.1	30.7	65.3	19.3	12.2	14.8
06 Oct	-	-	34.3	15.0	23.6	31.5	13.2	21.2	88.3	25.2	58.0	20.0	13.8	14.9
07 Oct	-	-	32.7	15.6	23.3	32.5	17.9	25.7	80.8	32.8	58.1	19.0	12.6	11.8
08 Oct	9.4	-	32.2	14.4	21.4	31.0	15.8	22.2	94.3	37.0	71.9	18.9	9.3	12.7
09 Oct	-	-	25.8	12.9	17.9	31.6	15.4	21.2	96.7	50.3	83.3	13.6	8.4	9.2
10 Oct	-	5.0	23.9	11.1	17.3	25.5	13.9	8.3	95.9	51.8	81.7	13.6	5.5	9.1
11 Oct	-	-	23.2	10.1	15.9	23.1	12.8	17.4	96.8	36.8	82.0	10.7	4.9	7.9
12 Oct	6.9	6.4	25.4	7.1	15.3	24.2	11.7	16.4	96.0	27.3	71.3	18.8	8.1	13.9
13 Oct	-	-	28.9	6.0	16.4	24.5	9.0	15.2	94.7	22.1	65.7	19.6	9.9	13.2
14 Oct	-	-	-	-	-	-	-	-	-	-	-	19.4	-	11.9
Total or Average	60.8	13.9	28.6	11.7	19.5	28.1	13.3	19.7	90.1	33.1	65.5	18.2	11.1	12.7

1/ Air temperature, relative humidity, solar radiation, and net radiation were measured at a 150 mm height above the soil surface.

Table 4. Daily soil temperatures at 10 and 30 mm soil depths for eight row cover treatments in the Fall 1986 at the Maricopa Agricultural Center.

	(A) No Cover[1/]						(B) Sorghum						(C) Agronet						(D) Reemay					
	1 cm			3 cm			1 cm			3 cm			1 cm			3 cm			1 cm			3 cm		
Date	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
30 Sep	38.0	16.8	27.4	33.6	19.2	26.4	33.2	15.9	24.6	30.1	17.2	27.3	43.3	18.6	31.0	37.2	20.0	28.6	38.6	20.4	29.5	33.5	22.3	27.9
01 Oct	27.0	12.5	19.8	25.2	14.0	19.6	26.0	13.7	19.9	24.7	16.8	20.8	32.0	14.9	23.5	30.3	16.1	23.2	30.7	15.0	22.9	28.3	16.4	22.4
02 Oct	25.3	13.3	19.3	24.0	15.1	19.6	24.4	14.6	18.2	23.5	15.7	18.6	27.9	14.3	21.1	26.9	15.4	21.2	29.7	16.0	22.9	24.6	17.3	21.0
03 Oct	27.5	12.4	20.0	26.1	13.1	19.6	25.7	13.9	18.0	24.0	14.9	18.3	32.2	13.9	23.0	41.3	14.3	28.1	29.1	15.0	22.1	26.2	16.0	21.2
04 Oct	29.7	11.4	20.6	27.2	12.5	19.9	27.2	12.8	18.8	25.0	14.0	18.9	35.1	13.5	24.3	32.6	14.5	23.6	31.9	14.1	23.0	28.6	15.1	21.9
05 Oct	25.3	14.6	20.0	24.1	15.6	19.9	25.0	15.4	19.3	23.6	16.2	19.5	28.7	15.7	22.2	27.6	16.5	22.1	27.3	16.9	22.1	25.4	17.5	21.5
06 Oct	30.8	13.5	22.1	28.7	14.1	21.4	28.1	14.9	20.2	25.9	15.8	20.2	36.1	14.9	25.5	33.7	15.7	24.7	33.0	15.1	24.1	29.4	16.0	22.7
07 Oct	33.0	15.6	22.7	30.5	16.3	22.6	28.1	17.4	22.9	26.0	18.2	22.7	36.7	16.6	23.9	34.7	17.3	23.9	33.2	17.1	24.1	27.7	17.8	23.6
08 Oct	31.5	16.1	22.4	29.3	17.1	22.4	27.3	16.8	21.0	25.8	17.6	21.1	37.4	17.1	24.3	35.3	17.8	24.3	33.4	17.8	24.5	30.2	18.4	24.1
09 Oct	32.2	15.4	21.1	29.0	16.5	21.3	26.7	16.8	20.3	25.0	17.7	20.5	36.4	16.8	22.5	34.3	17.6	22.7	32.0	17.5	23.0	28.9	18.4	23.0
10 Oct	27.7	14.6	19.2	25.5	16.1	19.5	22.5	15.8	18.7	22.0	16.8	19.0	31.3	15.8	20.6	29.6	16.8	20.9	29.2	17.5	21.2	26.7	17.8	21.4
11 Oct	25.8	12.6	17.7	22.8	13.9	18.0	20.7	14.5	17.2	20.2	15.3	17.6	29.6	14.0	18.8	26.9	14.4	19.1	26.2	15.0	19.5	23.9	15.7	19.8
12 Oct	27.8	11.7	18.0	25.7	12.8	18.2	22.6	14.0	17.2	21.5	14.8	17.5	32.7	13.5	20.0	30.8	14.3	20.0	29.6	14.1	20.2	26.2	14.9	20.0
13 Oct	27.6	9.0	17.1	25.4	10.2	17.4	21.8	11.8	15.9	20.7	12.9	16.4	31.0	11.7	18.8	29.2	12.6	19.0	28.4	11.6	19.5	25.4	12.9	19.4
14 Oct	30.0	8.6	18.1	27.4	9.8	18.1	24.2	11.1	17.7	22.5	12.3	17.4	32.8	10.7	19.4	30.7	11.7	19.4	29.7	11.1	19.6	26.0	12.3	19.4
Average	29.3	13.2	20.4	27.0	14.4	20.2	25.6	14.6	19.3	24.0	14.6	19.7	33.5	14.8	22.6	32.1	15.7	22.7	30.8	15.6	22.5	27.4	16.6	22.0

	(E) Polyshade Cloth						(F) Polyshade Cloth Strips						(G) American Straw Mat						(H) Straw					
	1 cm			3 cm			1 cm			3 cm			1 cm			3 cm			1 cm			3 cm		
Date	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
30 Sep	39.3	18.4	28.9	35.3	20.2	27.8	35.3	19.2	27.3	32.8	20.9	26.9	35.9	19.3	27.6	32.9	20.8	26.9	37.4	21.3	29.4	32.3	22.3	27.3
01 Oct	28.6	14.5	21.6	26.8	15.0	20.9	27.1	14.5	20.8	25.1	15.0	20.1	24.6	15.5	20.1	23.6	17.0	20.3	22.0	17.6	19.8	22.3	18.7	20.5
02 Oct	25.5	14.2	19.9	24.4	15.5	20.1	23.2	14.6	18.9	22.4	15.8	19.1	22.8	15.5	19.2	22.0	16.8	19.4	21.5	17.1	19.3	21.1	17.9	19.5
03 Oct	28.0	13.5	20.9	26.1	14.6	20.5	25.9	13.5	19.8	23.2	14.6	18.8	24.3	14.2	19.5	22.9	15.8	19.4	22.5	16.5	19.4	21.9	17.0	19.6
04 Oct	31.0	13.3	22.2	28.3	14.3	21.3	27.4	12.7	20.1	25.4	13.1	19.3	25.4	13.8	19.6	24.0	15.0	19.5	23.4	15.6	19.5	22.8	16.6	19.7
05 Oct	25.8	15.4	20.6	24.7	16.4	20.6	24.0	15.4	19.7	23.4	15.7	19.6	23.0	16.4	19.7	22.2	17.1	19.7	21.5	17.4	19.5	21.4	18.1	19.8
06 Oct	32.3	14.8	23.6	29.3	15.6	22.5	28.8	14.2	21.5	26.8	14.2	20.5	26.5	15.2	20.9	25.1	16.2	20.7	24.3	16.6	20.5	23.8	17.4	20.6
07 Oct	32.7	16.5	22.6	30.2	17.2	22.5	29.3	16.2	21.9	27.2	16.3	21.8	26.9	17.0	21.3	25.5	17.8	21.4	25.1	18.2	21.4	24.4	18.8	21.6
08 Oct	33.4	16.7	23.0	30.9	17.5	22.9	29.8	16.8	22.3	27.8	17.2	22.2	27.0	17.5	21.6	25.9	18.1	21.8	25.6	18.6	21.8	24.8	19.2	22.0
09 Oct	32.7	16.5	21.6	30.0	17.5	21.7	29.0	16.3	21.0	26.5	16.9	21.1	26.3	17.2	20.8	25.0	18.2	21.1	24.5	18.5	21.1	23.5	19.1	21.3
10 Oct	28.5	15.4	19.7	26.4	16.6	20.0	25.7	15.7	19.3	24.2	16.8	19.6	24.2	16.8	19.2	23.0	17.7	19.7	22.7	17.8	19.7	21.6	18.4	20.0
11 Oct	26.7	13.8	18.1	23.5	14.8	18.3	22.8	13.8	17.7	21.4	14.9	18.0	21.6	15.0	17.9	20.9	16.0	18.3	20.9	16.0	18.3	20.6	16.6	18.6
12 Oct	29.3	13.3	18.8	27.0	14.3	18.8	25.5	13.1	17.9	23.5	13.6	18.0	23.7	14.0	17.6	22.3	14.9	18.0	22.1	15.1	18.0	20.9	15.9	18.4
13 Oct	27.6	11.2	17.5	24.9	12.3	17.6	23.9	10.4	16.8	22.4	10.9	17.0	22.2	11.8	16.5	21.1	13.1	16.9	20.6	13.4	16.9	20.4	14.4	17.4
14 Oct	28.8	10.2	17.9	26.0	11.6	17.9	25.2	9.8	17.2	23.5	10.5	17.3	22.8	11.0	16.5	21.5	12.3	16.9	21.0	12.8	16.9	20.8	13.8	17.3
Average	30.0	14.5	21.1	27.6	15.6	20.9	26.9	14.4	20.1	25.0	15.1	20.0	25.1	15.3	19.9	23.9	16.4	20.0	23.7	16.8	20.1	22.8	17.6	20.2

1/ Guayule seeds were planted on September 30 and row cover treatments were installed in between 1000 and 1400 hours. Row cover treatments remained for the entire two-week period.

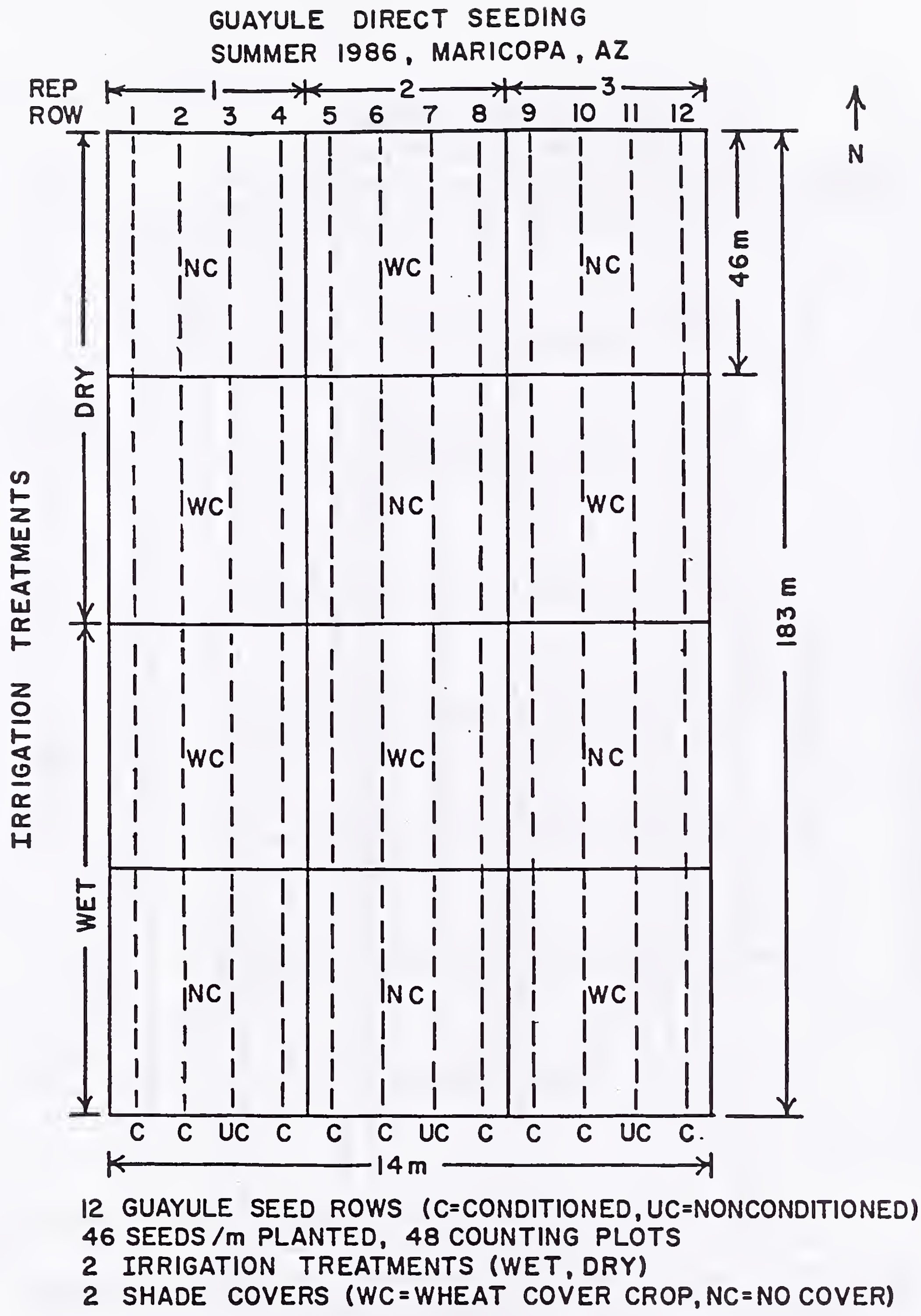
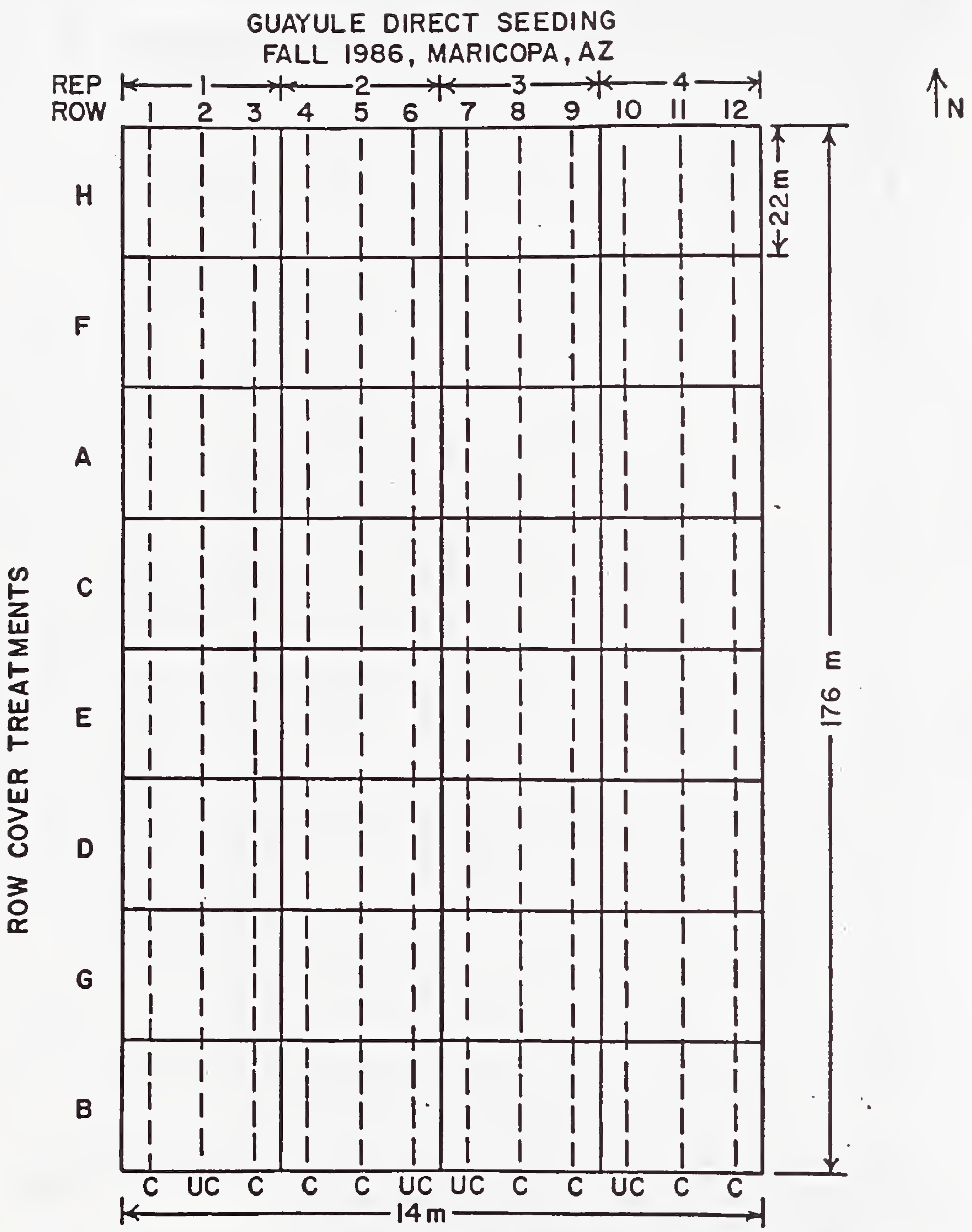


Figure 1. Field diagram showing two irrigation, two row cover, and two seed treatments in the Summer 1986 at the Maricopa Agricultural Center, Maricopa, Arizona.



12 GUAYULE SEED ROWS (C=CONDITIONED, UC = NONCONDITIONED),
46 SEEDS /m PLANTED, 64 COUNTING PLOTS

8 ROW COVER TREATMENTS:

A.CHECK
B.SORGHUM CROP
C.AGRONET (10% SHADE)
D.REEMAY (5% SHADE)
E.POLYSHADE CLOTH (40% SHADE)
F.POLYSHADE STRIPS (40% SHADE)
G.AMERICAN STRAW MAT
H.STRAW

Figure 2. Field diagram showing seven row cover and two seed treatments in the Fall 1986 at the Maricopa Agricultural Center, Maricopa, Arizona.

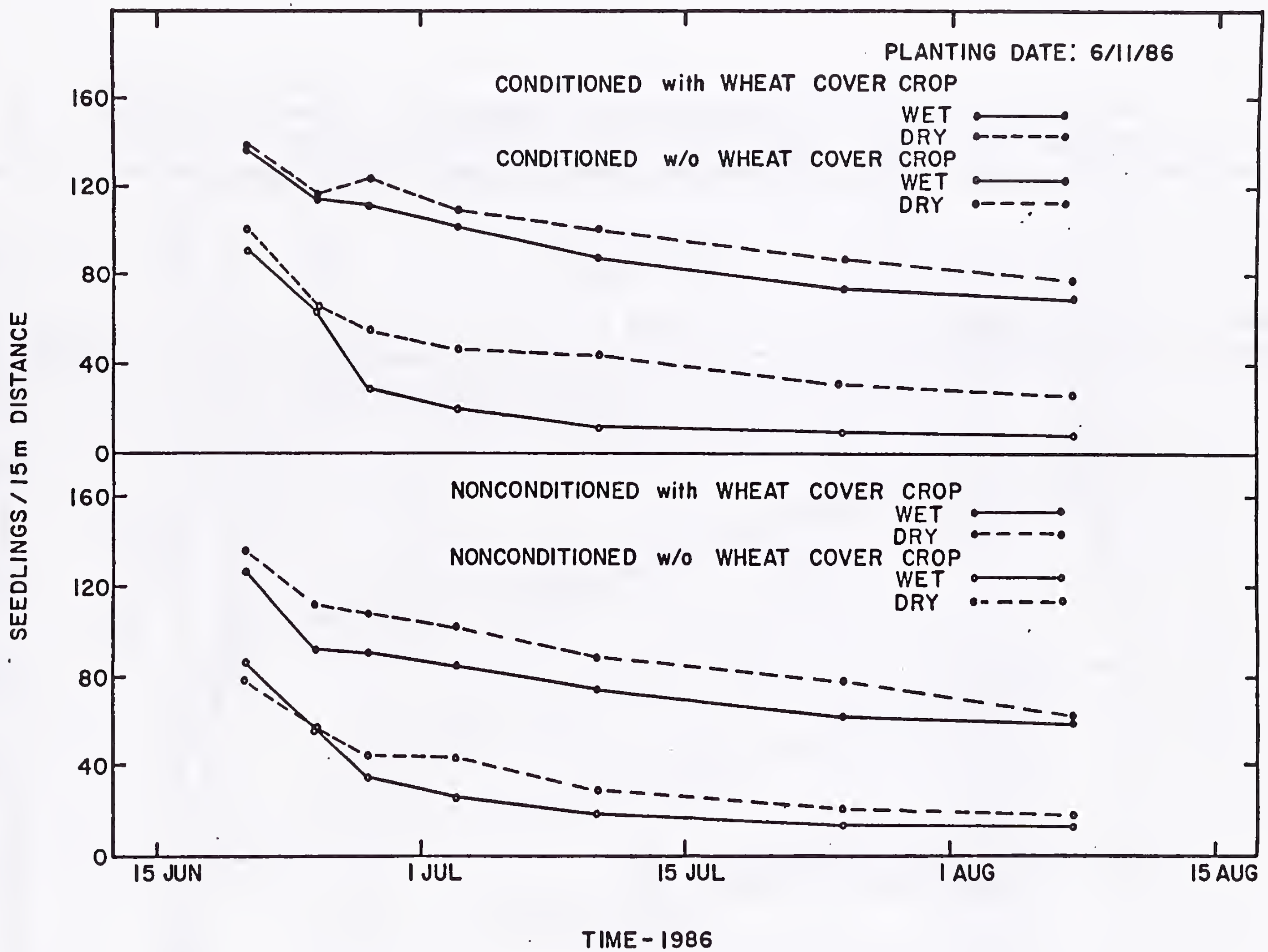


Figure 3. Guayule seedling counts per 15 meter distances versus time with a wheat cover and without a cover crop using conditioned and nonconditioned seeds in the Summer 1986 at the Maricopa Agricultural Center, Maricopa, Arizona.

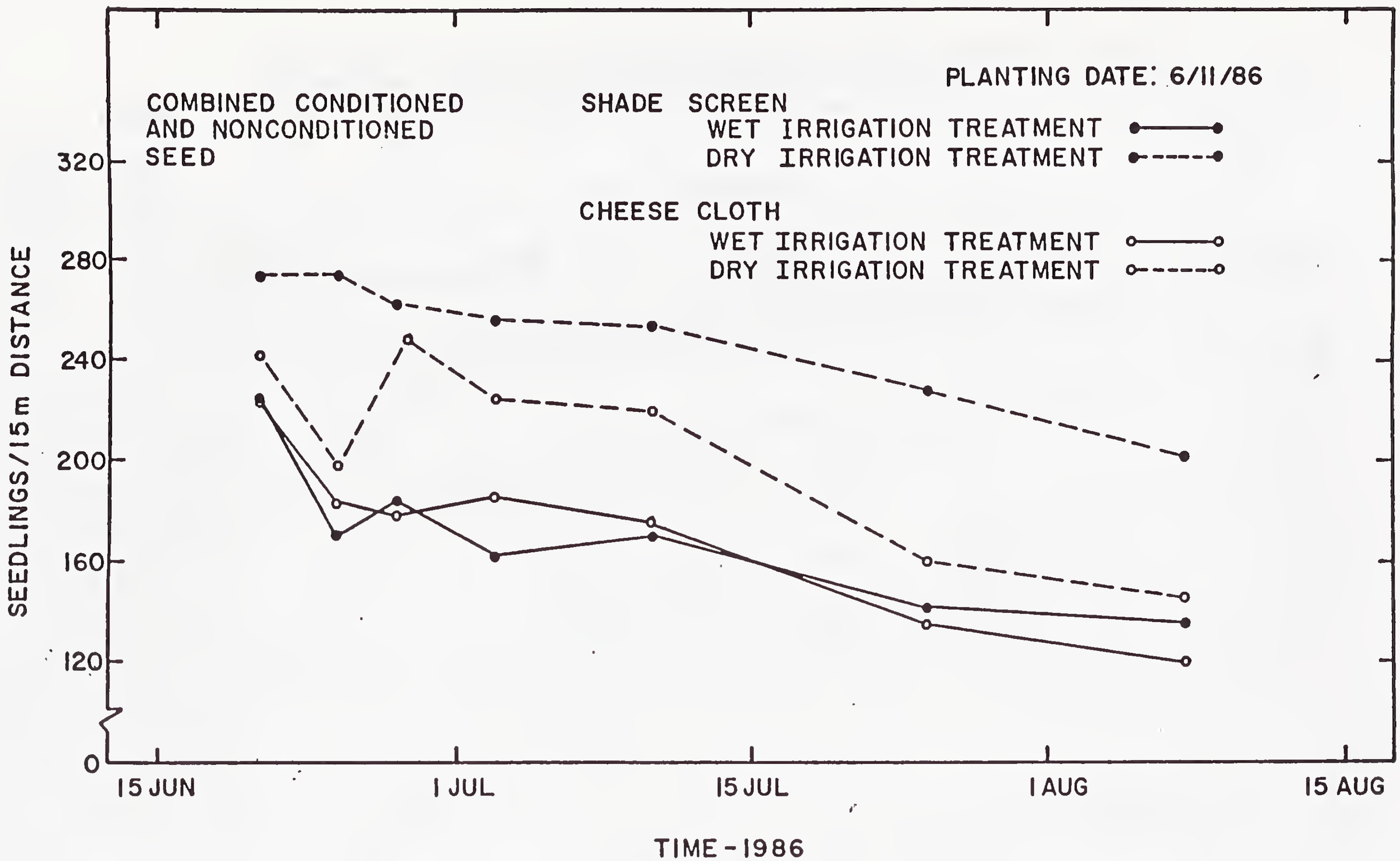


Figure 4. Guayule seedling counts per 15 meter distances versus time for two observational row cover treatments of polyshade and cheese cloth using conditioned and non-conditioned seeds in the Summer 1986 at the Maricopa Agricultural Center, Maricopa, Arizona.

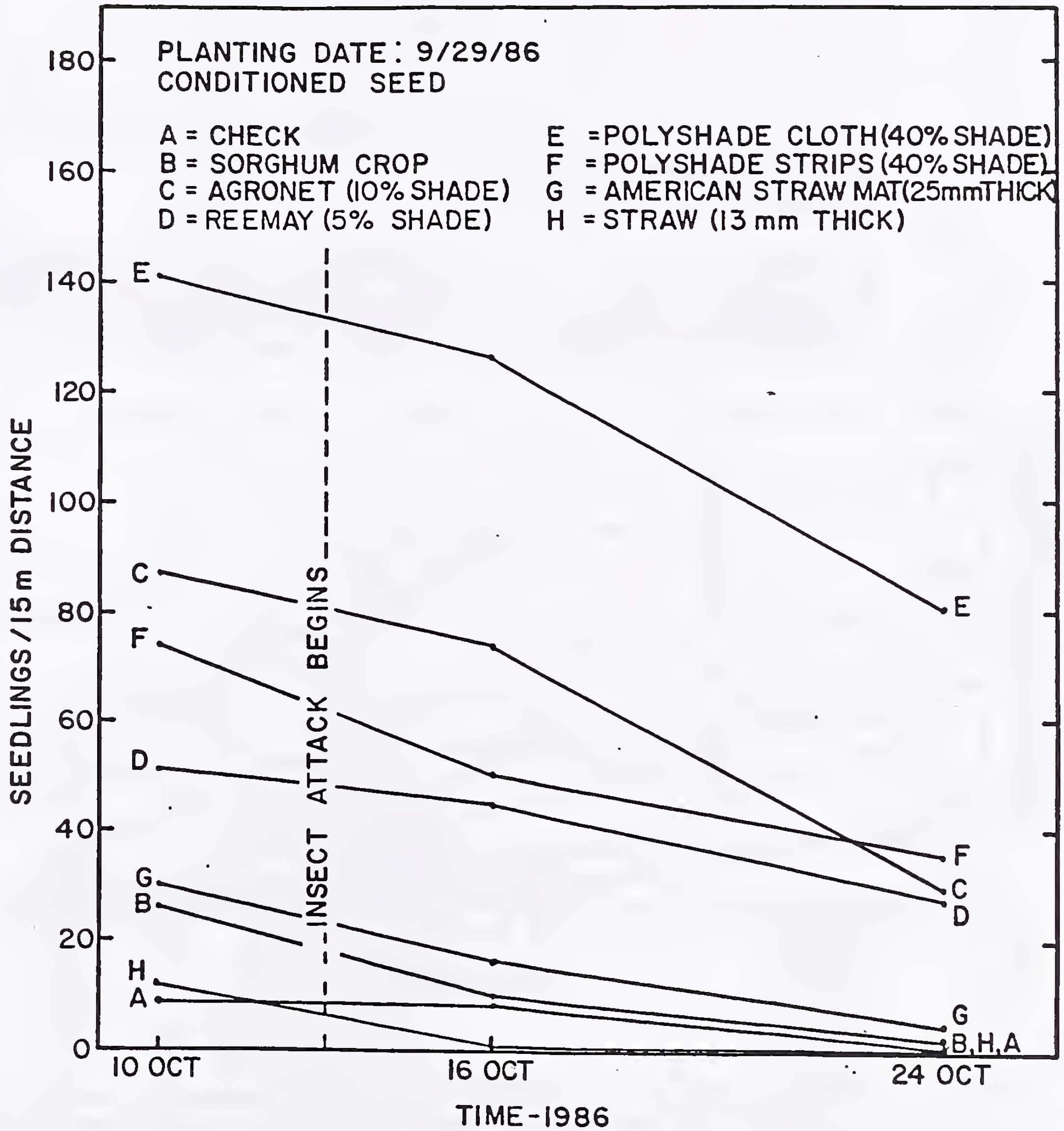


Figure 5. Guayule seedling counts per 15 meter distances versus time for eight row cover treatments using conditioned seeds in the Fall 1986 at the Maricopa Agricultural Center, Maricopa, Arizona.

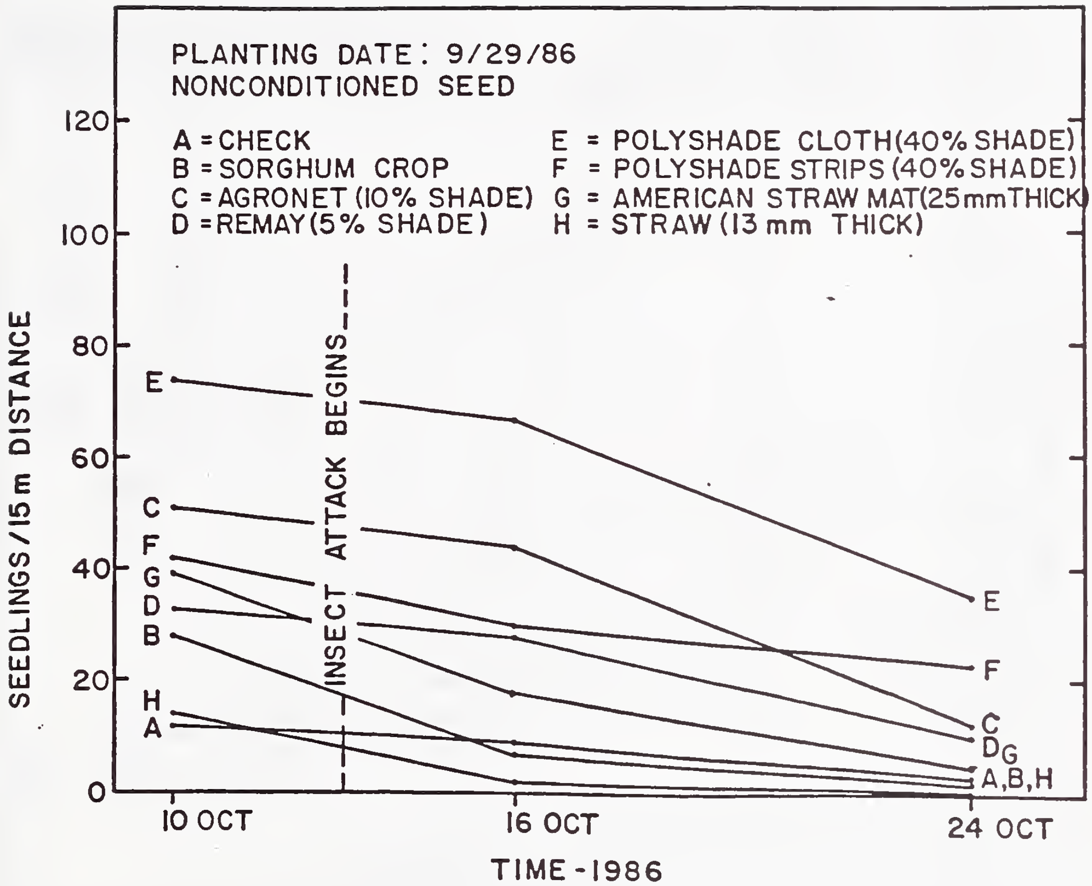


Figure 6. Guayule seedling counts per 15 meter distances versus time for eight row cover treatments using nonconditioned seeds in the Fall 1986 at the Maricopa Agricultural Center, Maricopa, Arizona.

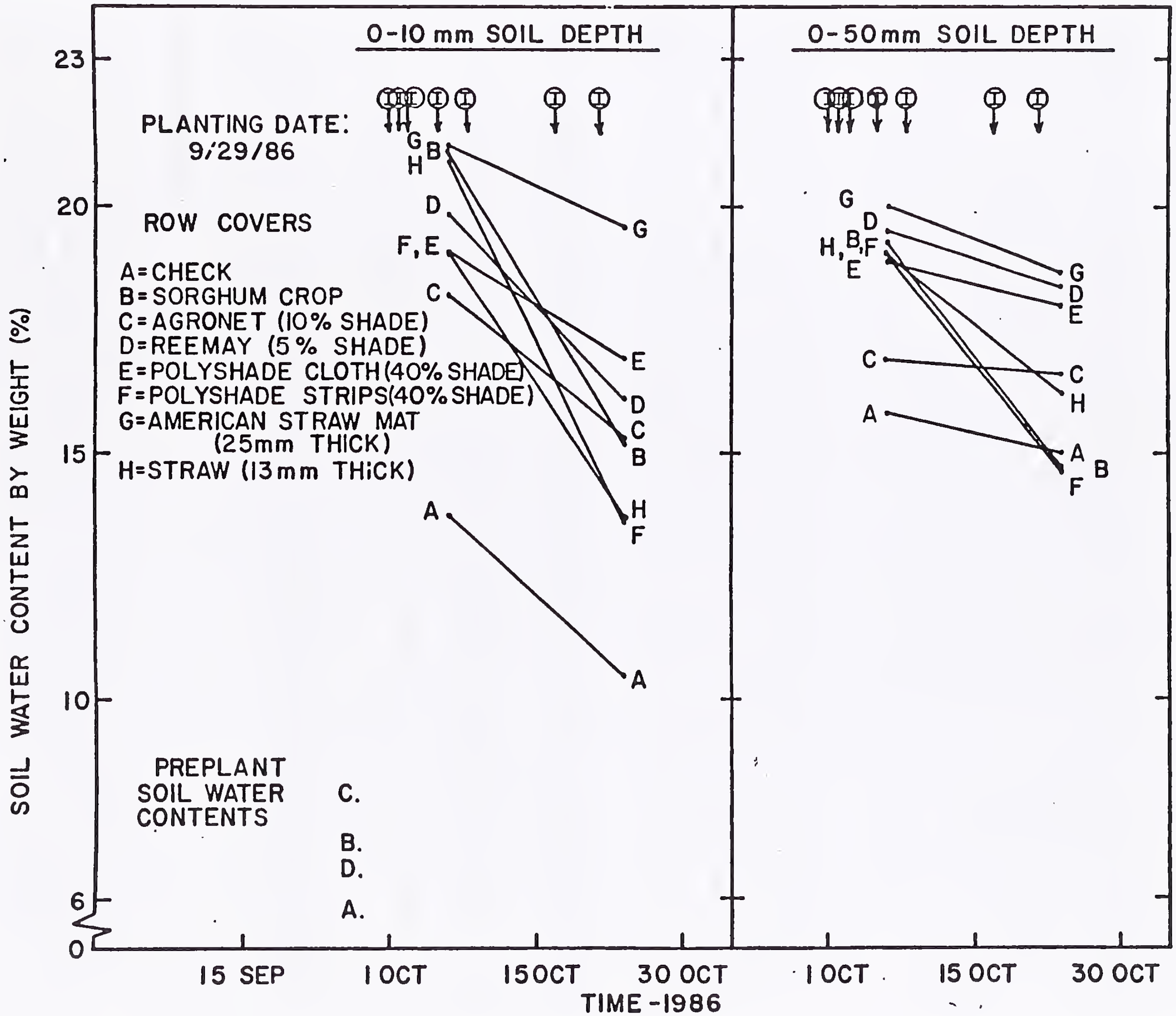


Figure 7. Soil water contents for eight row cover treatments in the Fall 1986 at the Maricopa Agricultural Center, Maricopa, Arizona.

TITLE: CANAL SYSTEM OPERATIONS

SPC: 1.3.03.1.f CRIS WORK UNIT: 5422-20740-013

INTRODUCTION

The operation of canal systems can significantly affect the ability of farmers to efficiently manage irrigation water, and to take advantage of new irrigation technology and management options. Irrigation deliveries should not vary in rate or volume from the quantities ordered by the farmers, but this is frequently not the case due to the delivery districts' inadequate control of canals. Water delivery policy should be as flexible as possible (essentially, water available "on demand") so that farmers can make the most efficient and economical use of the water, but present canal control schemes generally discourage flexibility because it would require larger canals, more labor, and expensive hardware.

The objectives of the canal system operations study are 1) to determine the sources of poor or non-uniform deliveries, and 2) to develop the techniques and structures required to provide uniform, flexible deliveries of water to farms. This will allow the farmers to make the most efficient use possible of irrigation water and at the same time allow economical and easy to manage operation of the delivery district. The three main research approaches followed in 1986 and which are on-going, are:

1) Detailed monitoring and analysis of lateral canal operations in the Wellton-Mohawk Irrigation and Drainage District in southwestern Arizona;

2) A similar study of large laterals, through cooperative efforts with the Imperial Irrigation District in southeastern California; and

3) A computer study of responses at flow furcations to non-steady conditions and transients.

Additionally, work continues on canal capacity requirements and the use of canals as regulating reservoirs, evaluation of canal control models produced outside the Laboratory, and development of constant head/constant flow structures.

WELLTON PROJECT

The Wellton-Mohawk Irrigation and Drainage District (WMIDD) provides Colorado River water to about 60,000 acres of farmland along the Gila River east of Yuma, AZ. The WMIDD is relatively efficient in overall water use, and has a fairly flexible delivery policy, providing generally 10 to 25 cfs to 5 to 20 acre, laser-levelled basins on three days' notice.

Lateral WM17.0 has been instrumented for monitoring since summer, 1985; it was selected because it is near the upstream end of the district where main canal levels could be expected to remain fairly steady, and non-uniformities in the lateral flow could be attributed primarily to

operations within the lateral. A second lateral at the downstream end of the district (M42.9) was selected for monitoring because main canal levels fluctuate widely at its heading and this fluctuation could be expected to influence the operation of the lateral. The M42.9 was to be instrumented during 1986, but budget constraints prevented this, although plumbing of the bubbler lines used to measure water levels has been completed, and most of the other required equipment has now been purchased. A number of flow measuring flumes must yet be constructed, but monitoring of the M42.9 should commence by June, 1987.

A three mile-long section of the WM17.0, from canal heading to the point beyond which typically only one delivery is made at a time, has 13 instrument centers which make a total of 38 measurements every 15 minutes. The measurements consist of inflow, all outflows, gate positions at check structures, canal levels just upstream of each outflow and check structure, and downstream canal levels where these levels can be expected to influence flow through an upstream check structure. Measurements are also taken at the heading of the sub-main Wellton canal (just downstream of the lateral WM17.0 heading at the Wellton-Mohawk main canal) to monitor the operation of a Danaidean controlled-leak constant downstream head device. An additional measurement will be made in 1987 once flumes have been constructed at site WM17.0-2.1L, a new farm offtake that became operational during 1986.

In 1986 a great deal was learned about operating the data measuring-logging-recording system using double-bubbler and microprocessor-based technologies. Failures of equipment occurred frequently, but regular maintenance prevented large-scale losses of data at particular measuring sites. As a result of this experience, and through consultation with equipment manufacturers, some hardware changes have been made, and revised maintenance procedures implemented. These changes should ensure fewer problems at the WM17.0 and new installations. Table 1 summarizes data logger failures from July, 1985 through October, 1986, and Table 2 summarizes other equipment failures for this period.

Data are recorded in the field on solid state EPROMs which are exchanged approximately every three weeks. Data are downloaded to a PC-type micro-computer for processing and analysis, and are transferred to streamer tape cassettes for permanent storage. Table 3 lists the measurement site descriptions for the WM17.0, and Table 4 outlines the file naming conventions for the raw data. Table 5 shows the flow of data through the various processing programs, whose operations are described in the following paragraphs.

The first step in processing the data is to run the original, raw reports (the "W1" files, for WM17.0 data) through a FORTRAN program called HQSMO which edits out erroneous or unmeasured reports in the files, recomputes the good data on the basis of a moving average of pressure transducer slope, and writes an edited, smoothed output file (the "W2" files, for WM17.0 data). The second step is to prepare the data for entry into databases of various configuration, by separating the edited and smoothed files into their component columns, and creating an individual file for each measuring site for month-long periods. This is done with another FORTRAN program call CDBW, which also abbreviates the output files by

removing the strings of zeroes that represent unrecorded and erroneous reports in the HQSMO-produced files. Additionally, CDBW converts bubbler readings from depth of water on the bubbler, to absolute water depth or gate opening as appropriate. Table 6 outlines the naming conventions for these database-ready files, Table 7 lists the site descriptions for the WM17.0, and Table 8 has measurement type descriptions. The information in these three tables is used in CDBW and the remaining data processing programs.

The files produced by CDBW (the "I" files, for WM17.0 data) are then submitted to the FORTRAN program CMDU, which identifies all deliveries into and out of the monitored length of canal in a specified month, and calculates average flow rate, volume of water applied, and coefficients of variability for 100, 99, 98, 95, and 90 percent of the total delivery volume. The coefficients of variability are indicative of the uniformity of a particular delivery. CMDU prints a summary report of all measured flow activity along a canal in a given month in a format that allows identification of those CDBW-produced files that need additional editing; when editing is complete, CMDU is run a final time to produce a permanent record. The CDBW-produced files are then submitted to yet another FORTRAN program call CMSD which accumulates the summary discharge statistics from month to month (these files have the prefix "SUM"). Yearly flow summary reports are produced with FORTRAN program CMSM. The HQSMO- and CDBW-produced files are stored permanently on streamer cassette tape at this point.

Graphical representation of the canal monitoring data is proving to be extremely valuable for identifying operations activities, cause and effect relations, and data sets deserving the most intense study. To this end, two more programs were written: CMPLT, a FORTRAN program, selects any (up to eight) monitored measurements for a given month, and arrays the data for MGRAPH, a PASCAL program, which can plot the data in a number of combinations. In this way, for example, deliveries can be contrasted with total lateral inflow and outflow, or pool levels compared to check gate operations. FORTRAN program CMFB computes flow balance for month-long periods, based on the difference between inflow and total measured outflows, and this information is available for plotting with CMPLT and MGRAPH. The flow balance is useful for determining the accuracy of the various flumes, identifying transients, and locating deliveries not recorded due to hardware failures in the field.

With an arsenal of data reduction tools now in hand, a detailed investigation of farm delivery uniformity is underway. Using regression analysis, uniformity as measured by coefficients of variability is being studied for the influence of: time of year; crop grown at a turnout, and cropping patterns in the lateral-served land as a whole; delivery flow rate; total incoming flow on the lateral; location along the lateral and within a pool; number and location of concurrent events; and canal operator (regular or relief ditchrider). Through study of WMIDD records, a comparison will be made of water ordered by the farmer, water measured, and water charged to the farmer. It is anticipated that for the 1988 irrigation season, some structural improvements such as flumes with gauges, or constant discharge devices, will be installed to test recommendations for reducing variability in the delivery of water to the farm.

IMPERIAL PROJECT

Two lateral canals off the East Highline canal, Myrtle and Munyon, were chosen by the Imperial Irrigation District (IID) for their canal monitoring project. Flumes were constructed (by IID) at the heading and spill of each canal so that flow into and out of the canal could be measured. Of the 51 farm turnouts on these two canals, only 7 had flumes already installed. Thus it was decided that instead of placing flumes on all farm canals, as in the Wellton project, flumes would be placed within the lateral canals at about every fourth or fifth check structure. Seven inline flumes (in addition to the headings and spills) were constructed by IID in the two laterals.

IID installed 29 loggers to monitor 44 water depths on the Myrtle covering 17 of the 26 delivery points and 27 loggers to monitor 38 water depths on the Munyon covering 14 out of 25 delivery points. Water levels are being monitored with float operated potentiometers mounted in stilling wells. IID thus installed a total 82 stilling wells. Other stilling wells and flumes will be installed as farmer permission and time permit.

Site descriptions for the logger data are given in Table 9. The data include canal, logger number, logger output column number, data type and word description. Data type codes are explained in Table 8. A proposed file naming convention is shown in Table 10 for the monthly data files, where the data is put in relational data base form for each logger data column.

Data collection began in June of 1986. Carl Arterberry, ARS Brawley (but part of USWCL staff), has been collecting the EPROMs from the data loggers and transferring the data to raw data files. IID has compared fluctuations in lateral heading flow rates and fluctuations in main canal water levels. They have concluded that through periodic manual adjustments to discharge by hydrographers, lateral flow rates are not significantly affected by main canal level fluctuations. Data analysis programs are still being prepared for USWCL analysis. The analysis will follow similar lines to the Wellton project. The biggest difficulty with this data is that the canals flow continuously over most of the year, and when looking at inflow and outflow for a given reach between two in-line flumes it is difficult to sort between canal transients and delivery nonuniformity. Such sorting is possible through the use of water surface data, but will take time.

Current plans are to continue data collection through 1987.

FURCATION FLEXIBILITY PROJECT

Furcation flexibility refers to the manner in which a flow control structure divides error or transients among the branches of a canal furcation. Manipulation of furcation flexibility can be an important tool in evaluating and implementing alternative canal operations techniques for reducing delivery variability and water waste. Often, existing structures (for instance, the weir-sluice gate combinations common in the southwest) can be adjusted in a number of configurations that divide flow

similarly under steady conditions, but which act quite differently in response to transients. A computer study is being made of the flexibility of common irrigation canal structures with the objective of recommending how they might be configured for better management. The results of this work will mesh with other recommendations coming out of the delivery uniformity study.

SUMMARY

The canal system operations study is providing a detailed picture of how lateral canals are operated to deliver water to farm fields. If the deliveries are uniform and available under a flexible policy regarding rate, frequency, and duration, farmers can take maximum advantage of changing irrigation techniques and management options. In practice, most delivery districts do not have flexible policies and deliveries are frequently not uniform, because of an inability to economically and easily exercise adequate control of the canals. To study this problem, intensive monitoring of lateral canals in the Wellton-Mohawk Irrigation and Drainage District in Arizona, and the Imperial Irrigation District in California is ongoing. Analysis of measured flows, canal levels, and gate positions is revealing the sources of non-uniform deliveries, and pointing the way toward improved structures and operational techniques to provide better on-farm water management and economical delivery system control methods.

PERSONNEL

J. D. Palmer, A. J. Clemmens, J. A. Replogle, A. R. Dedrick, R. Kapfer, J. Padilla, R. J. Gerard.

Table 1. Summary of Data Logger Failures, WM17.0, July 1985 through October 1986. Thirty-three visits to the project site occurred during this period, at an average interval of 15 days.

FAILURE CODE	NUMBER OF OCCURRENCES	DESCRIPTION
1	12	Batteries dead due to too long a service interval.
2	2	EPROM empty; setups correct but had not recorded any logs since last visit.
3	15	Time to next scan greater than 15 minutes; unit not logging or writing to report.
4	17	Pump battery dead; 6v battery that drives pump dead but second 6v battery that operates logger still well-charged; indicative of failure Mode 5.
5	20	Runaway pump; pump running continuously irrespective of scan times.
6	14	Clock and calendar readings on report faulty.
7	5	"Not logging" message and EPROM empty; logger apparently turned off immediately after previous visit.
8	6	"Not logging" message and some EPROM volume; logger apparently turned off some time after previous visit.
9	11	Specific options not accessible (e.g., Log Start/Stop, Show Data).
10	5	Gray display on terminal; logger locked up, no access possible without complete power down and loss of programming.
11	6	Program elements missing or faulty (e.g., sensor definitions, report settings, functions).
12	8	Data written to more than one file, sometimes with loss of data between.
13	3	Data written to report beyond time of visit; phantom data for sometimes weeks beyond time EPROM was removed.

Table 2. Summary of Non-Logger Failures, WM17.0, July 1985 through October 1986. Thirty-three visits to the project site occurred during this period, at an average interval of 15 days.

FAILURE CODE	NUMBER OF OCCURENCES	DESCRIPTION
1	34	Pump found failed and/or replaced.
2	23	Single measurement bubbler line detached or destroyed (cut or burnt).
3	1	Double-bubbler line detached or destroyed.
4	2	Valve-switching interface failed.
5	2	Three-way solenoid valve failed.

Table 3. Measurement Site Descriptions for WM17.0 Canal Monitoring Project. "Column" is the number of the data column on the original logger output report; columns 1 and 2 always contain pressure transducer slopes (mv/ft) and intercepts (mv), respectively.

SITE	LOGGER	COLUMN	UNITS	DESCRIPTION
WH	01	3	ft	upstream head (Wellton-Mohawk)
		4	ft	downstream head (Wellton)
		5	ft	float head (Danaidean gate)
		6	ft	floatwell head (Danaidean gate)
0.6	02	3	ft	upstream head (division box)
		4	ft	left check gate head
		5	ft	right check gate head
		6	cfs	0.6L farm offtake flow
		7	cfs	0.6CK (downstream) flow
		8	cfs	0.6Lat (sublateral) flow
		9	ft	constant head orifice head
0.9	03	3	ft	upstream head
		4	ft	left check gate head
		5	ft	right check gate head
		6	cfs	0.9R farm offtake flow
1.0	04	3	ft	upstream head
		4	ft	left check gate head
		5	ft	right check gate head
		6	cfs	1.0L farm offtake flow
1.2	05	3	ft	upstream head
		4	cfs	1.2L farm offtake flow
1.4	06	3	ft	upstream head
		4	ft	left check gate head
		5	ft	right check gate head
		6	cfs	1.4L farm offtake flow
		7	ft	downstream head
1.9	07	3	ft	upstream head
		4	cfs	1.9L farm offtake flow
2.1	08	3	ft	upstream head
		4	ft	left check gate head
		5	ft	right check gate head
		6	ft	downstream head
2.4	09	3	ft	upstream head
		4	cfs	2.4L farm offtake flow

Table 3. (cont.)

2.6	10	3	ft	upstream head
		4	ft	check gate head
		5	ft	downstream head
2.9	11	3	ft	upstream head
		4	cfs	2.9R farm offtake flow
3.0CK	12	3	ft	upstream head
		4	ft	check gate head
		5	cfs	continuing lateral flow
3.0L	13	3	cfs	3.0L farm offtake flow

Table 4. File Naming Convention for Raw Data, Wellton Canal Monitoring Project.

File name: AbCCdd

Where
- A = Lateral canal initial
- b = File type
- CC = Instrument site
- dd = Data collection period

Lateral canal initial: W = WM17.0
M = M42.9

File type: 1 = original raw data
2 = smoothed and edited raw data

Instrument site:

For WM17.0	For M42.9
01 = Wellton Canal Heading	01 = M42.9 Heading
02 = WM17.0-0.6	02 = M42.9-0.3
03 = WM17.0-0.9	03 = M42.9-1.2
04 = WM17.0-1.0	04 = M42.9-1.3
05 = WM17.0-1.2	05 = M42.9-1.5
06 = WM17.0-1.4	06 = M42.9-1.6
07 = WM17.0-1.9	07 = M42.9-1.8
08 = WM17.0-2.1	08 = M42.9-2.1/-2.2
09 = WM17.0-2.4	09 = M42.9-2.1LAT-0.7
10 = WM17.0-2.6	10 = M42.9-2.1LAT-0.9
11 = WM17.0-2.9	11 = M42.9-2.1LAT-1.2
12 = WM17.0-3.0CK	12 = M42.9-2.7
13 = WM17.0-3.0L	13 = M42.9-2.9LAT
	14 = M42.9-3.2
	15 = M42.9-3.4/-3.3LAT

Data collection period: (for WM17.0)

03 - 7/12/85 to 8/ 1/85	04 - 8/ 1/85 to 8/26/85
05 - 8/26/85 to 9/12/85	06 - 9/12/85 to 10/ 9/85
07 - 10/ 9/85 to 11/ 6/85	08 - 11/ 6/85 to 11/21/85
09 - 11/21/85 to 12/12/85	10 - 12/12/85 to 1/ 3/86
11 - 1/ 3/86 to 1/22/86	12 - 1/22/86 to 2/11/86
13 - 2/11/86 to 3/ 5/86	14 - 3/ 5/86 to 3/20/86
15 - 3/20/86 to 4/ 4/86	16 - 4/ 4/86 to 4/23/86
17 - 4/ 4/86 to 5/ 9/86	18 - 5/ 9/86 to 5/27/86
19 - 5/27/86 to 6/11/86	20 - 6/11/86 to 6/25/86
21 - 6/25/86 to 7/16/86	22 - 7/16/86 to 8/ 6/86
23 - 8/ 6/86 to 8/27/86	24 - 8/27/86 to 9/17/86
25 - 9/17/86 to 10/ 8/86	26 - 10/ 8/86 to 11/ 3/86
27 - 11/ 3/86 to 11/20/86	28 - 11/20/86 to 12/ 8/86
29 - 12/ 8/86 to 12/23/86	30 - 12/23/86 to 1/ 7/87
31 - 1/ 7/87 to 1/29/87	32 - 1/29/87 to 2/ /87

Table 4. (cont.)

Example: W10922

W - Lateral WM17.0
1 - Original raw data
09 - Site WM17.0-2.4
22 - Data collected 7/16/86 to 8/6/86

Table 5. Flow of Wellton Monitoring Data Through Processing Programs

INPUT	PROGRAM	OUTPUT
Raw data logger files ("W1" files)	HQSMO	Smoothed and edited files ("W2" files)
"W2" files	CDBW	Individual database files ("I" files)
"I" files	CMDU	Delivery uniformity statistics report
"I" files	CMSD	Delivery uniformity summary files ("SUM")
"SUM" files	CMSM	Yearly delivery summary report
"I" files	CMFB	Monthly flow balance files ("F" files)
"I" or "F" files	CMPLT	Temporary plot file ("PLOTWD")
"PLOTWD" file	MGRAPH	Levels and flows plots

Table 6. File Naming Convention for Processed Data, Wellton Canal Monitoring Project.

File name: AbCdEE

Where:

A	=	Canal letter
b	=	Logger site letter
C	=	Measurement column number (from HQSMO files)
d	=	Year number
EE	=	Month number

Canal letter:
I = WM17.0
K = M42.9

Logger site letter:

For WM17.0	For M42.9
A = Wellton Canal Heading	A = M42.9 Heading
B = WM17.0-0.6	B = M42.9-0.3
C = WM17.0-0.9	C = M42.9-1.2
D = WM17.0-1.0	D = M42.9-1.3
E = WM17.0-1.2	E = M42.9-1.5
F = WM17.0-1.4	F = M42.9-1.6
G = WM17.0-1.9	G = M42.9-1.8
H = WM17.0-2.1	H = M42.9-2.1/-2.2
I = WM17.0-2.4	I = M42.9-2.1LAT-0.7
J = WM17.0-2.6	J = M42.9-2.1LAT-0.9
K = WM17.0-2.9	K = M42.9-2.1LAT-1.2
L = WM17.0-3.0CK	L = M42.9-2.7
M = WM17.0-3.0L	M = M42.9-2.9LAT
	N = M42.9-3.2
	P = M42.9-3.4/-3.3LAT

Measurement column number (typical, depends on instrument site):
1 - head upstream of check structure
2 - left check gate head
3 - right check gate head
4 - farm offtake flow
5 - head downstream of check structure
6 - miscellaneous

Year number:
5 - 1985
6 - 1986
7 - 1987
etcetera

Month number: 01 - January, through 12 - December

Example: IB4508
I - canal WM17.0
B - site WM17.0-0.6
4 - measurement column for WM17.0-0.6L farm offtake flow
5 - 1985
08 - August

Table 7. Site Descriptions for Individual Measurements, for Processed WM17.0 Data Files. "Column" refers to the data location in the HQSMO-produced files (the "W2" files).

CANAL	SITE	COLUMN	TYPE	DESCRIPTION
I	A	1	A	Wellton-Mohawk Canal level
		2	B	Wellton Canal level
		3	K	Gate-positioning float level
		4	M	Float chamber level
I	B	1	A	-0.6 upstream level
		2	K	-0.6 left check gate opening
		3	K	-0.6 right check gate opening
		4	G	-0.6L farm delivery flow
		5	D	-0.6CK flow (main lateral flow)
		6	J	-0.6LAT flow
		7	L	CHO on -0.6LAT level
I	C	1	A	-0.9 upstream level
		2	K	-0.9 left check gate opening
		3	K	-0.9 right check gate opening
		4	G	-0.9R farm delivery flow
I	D	1	A	-1.0 upstream level
		2	K	-1.0 left check gate opening
		3	K	-1.0 right check gate opening
		4	G	-1.0L farm delivery flow
I	E	1	A	-1.2 upstream level
		2	G	-1.2L farm delivery flow
I	F	1	A	-1.4 upstream level
		2	K	-1.4 left check gate opening
		3	K	-1.4 right check gate opening
		4	G	-1.4L farm delivery flow
		5	B	-1.4 downstream level
I	G	1	A	-1.9 upstream level
		2	G	-1.9L farm delivery flow
I	H	1	A	-2.1 upstream level
		2	K	-2.1 left check gate opening
		3	K	-2.1 right check gate opening
		4	B	-2.1 downstream level
I	I	1	A	-2.4 upstream level
		2	G	-2.4L farm delivery flow
I	J	1	A	-2.6 upstream level
		2	K	-2.6 check gate opening
		3	B	-2.6 downstream level
I	K	1	A	-2.9 upstream level
		2	G	-2.9R farm delivery flow
I	L	1	A	-3.0CK upstream level
		2	K	-3.0CK check gate opening
		3	D	-3.0CK continuing lateral flow
I	M	1	G	-3.0L farm delivery flow

Table 8. Descriptions of Data Types for Canal Monitoring Project

DATA TYPE	UNITS	DESCRIPTION
A	FT	In-line canal depth u/s of check gate (pond)
B	FT	In-line canal depth d/s of check gate
C	FT	In-line elev d/s of check gate (ref. to u/s)
D	CFS	In-line flume discharge downstream of check
E	FT	Delivery canal depth (-1.0 ft for Imperial)
F	FT	Delivery canal elev (referenced to u/s pond)
G	CFS	Delivery flume discharge
H	FT	Lateral-offtake canal depth
I	FT	Lateral-offtake canal elev (ref. to u/s pond)
J	CFS	Lateral-offtake flume discharge
K	FT	Gate opening
L	FT	Constant Head Orifice head
M	FT	Floatwell head
N	MV	Transducer offset
O	MV/FT	Transducer gain

Table 9. Site Data Descriptions for Imperial Canal Monitoring Project Raw Data.

CANAL	LOGGER	COL	TYPE	DESCRIPTION
MY	01	1	A	EHL Depth at Myrtle
MY	02	1	A	My Pond 1 depth
MY	02	2	E	My Del 1 depth
MY	02	3	F	My Del 1 backwater
MY	03	1	B	My Pond 1 d/s depth
MY	03	2	D	My Pond 1 d/s flow
MY	05	1	E	My Del 1-A depth
MY	05	2	F	My Del 1-A backwater
MY	04	1	A	My Pond 1-A depth
MY	07	1	E	My Del 2 depth
MY	07	2	F	My Del 2 backwater
MY	06	1	A	My Pond 2&3 depth
MY	06	2	E	My Del 3 depth
MY	06	3	F	My Del 3 backwater
MY	09	1	E	My Del 4 depth
MY	09	2	F	My Del 4 backwater
MY	08	1	A	My Pond 4 depth
MY	10	1	A	My Pond 5 depth
MY	10	2	B	My Pond 5 d/s depth
MY	10	3	D	My Pond 5 d/s flow
MY	10	4	E	My Del 5 depth
MY	10	5	F	My Del 5 backwater
MY	11	1	A	My Pond 7 depth
MY	11	2	E	My Del 7 depth
MY	11	3	F	My Del 7 backwater
MY	12	1	A	My Pond 9 depth
MY	12	2	E	My Del 9 depth
MY	12	3	F	My Del 9 backwater
MY	14	1	E	My Del 10 head
MY	14	2	F	My Del 10 backwater
MY	13	1	A	My Pond 10&11 depth
MY	13	2	E	My Del 11 depth
MY	13	3	F	My Del 11 backwater
MY	15	1	A	My Pond 13 depth
MY	15	2	B	My Pond 13 d/s depth
MY	15	3	D	My pond 13 d/s flow
MY	15	4	E	My Del 13 depth
MY	15	5	F	MY Del 13 backwater
MY	17	1	E	My Del 14 depth
MY	17	2	F	My Del 14 backwater
MY	16	1	A	My Pond 14&15 depth
MY	16	2	E	My Del 15 depth
MY	16	3	F	My Del 15 backwater
MY	16	4	G	My Del 15 flow
MY	19	1	E	My Del 16 depth
MY	19	2	F	My Del 16 backwater
MY	18	1	A	My Pond 16&17 depth

Table 9. (cont.)

MY	18	2	E	My Del 17 depth
MY	18	3	F	My Del 17 backwater
MY	18	4	G	My Del 17 flow
MY	20	1	A	My Pond 18&18A depth
MY	20	2	B	My Pond 18 d/s depth
MY	20	3	D	My Pond 18 d/s flow
MY	20	4	E	My Del 18 depth
MY	20	5	F	My Del 18 backwater
MY	20	6	G	My Del 18 flow
MY	21	1	A	My Pond 19 depth
MY	21	2	E	My Del 19 depth
MY	21	3	F	My Del 19 backwater
MY	21	4	G	My Del 19 flow
MY	22	1	A	My Pond 21 depth
MY	23	1	A	My Pond 22 depth
MY	23	2	B	My Pond 22 d/s depth
MY	23	3	D	My Pond 22 d/s flow
MY	24	1	A	My Pond 23 depth
MY	25	1	A	My Pond 24 depth
MY	26	1	A	My Pond 25 depth
MY	27	1	A	My Pond 26 depth
MY	28	1	A	My Pond 27&28 depth
MY	29	1	B	Myrtle spill head
MY	29	2	D	Myrtle spill flow
MU	30	1	A	EHL depth at Munyon
MU	31	1	A	Mu Pond 1 depth
MU	32	1	B	Mu Pond 1 d/s depth
MU	32	2	D	Mu Pond 1 d/s flow
MU	34	1	E	Mu Del 3 depth
MU	34	2	F	Mu Del 3 backwater
MU	33	C	D	Mu Pond 2&3 depth
MU	33	2	E	Mu Del 2 depth
MU	33	3	F	Mu Del 2 backwater
MU	36	1	E	Mu Del 4-A depth
MU	36	2	F	Mu Del 4-A backwater
MU	35	1	A	Mu Pond 4&4A depth
MU	35	2	E	Mu Del 4 depth
MU	35	3	F	Mu Del 4 backwater
MU	35	4	G	Mu Del 4 flow
MU	38	1	E	Mu Del 5 depth
MU	38	2	F	Mu Del 5 backwater
MU	37	1	A	Mu Pond 5&6 depth
MU	37	2	E	Mu Del depth
MU	37	3	F	Mu Del 6 backwater
MU	39	1	A	Mu Pond 9 depth
MU	39	2	B	Mu Pond 9 d/s depth
MU	39	3	D	Mu Pond 9 d/s flow
MU	41	1	E	Mu Del 12 depth
MU	41	2	F	Mu Del 12 backwater
MU	40	1	A	Mu Pond 11 depth
MU	40	2	E	Mu Del 11 depth

Table 9. (cont.)

MU	40	3	F	Mu Del 11 backwater
MU	42	1	A	Mu Pond 13 depth
MU	42	2	E	Mu Del 13 depth
MU	42	3	F	Mu Del 13 backwater
MU	42	4	G	Mu Del 13 flow
MU	43	1	A	Mu Pond 14 depth
MU	43	2	E	Mu Del 14 depth
MU	43	3	F	Mu Del 14 backwater
MU	43	4	G	Mu Del 14 flow
MU	44	1	B	Mu Pond 14 d/s depth
MU	44	2	D	Mu Pond 14 d/s flow
MU	46	1	E	Mu Del 15-E depth
MU	46	2	F	Mu Del 15-E backwater
MU	45	1	A	Mu Pond 15 depth
MU	45	2	E	Mu Del 15-W depth
MU	45	3	F	Mu Del 15W backwater
MU	47	1	A	Mu Pond 16 depth
MU	48	1	A	Mu Pond 21 depth
MU	48	2	E	Mu Del 21 depth
MU	48	3	F	Mu Del 21 backwater
MU	49	1	A	Mu Pond 22 depth
MU	49	2	E	Mu Del 22 depth
MU	49	3	F	Mu Del 22 backwater
MU	50	1	A	Mu Pond 23 depth
MU	50	2	B	Mu Pond 23 d/s depth
MU	50	3	D	Mu Pond 23 d/s flow
MU	51	1	A	Mu Pond 24 depth
MU	52	1	A	Mu Pond 25 depth
MU	53	1	A	Mu Pond 26 depth
MU	54	1	A	Mu Pond 27 depth
MU	55	1	A	Mu Pond 28 depth
MU	56	1	B	Munyon spill depth
MU	56	2	D	Munyon spill flow

Table 10. File Naming Convention for Imperial Canal Monitoring Project Raw Data

File name: AAbbCdEE

Where:

AA	=	Canal abbreviation
bb	=	Logger number
C	=	Data column from logger
d	=	Year number
EE	=	Month number

Canal abbreviation:

MY - Myrtle lateral
MU - Munyon lateral

Logger number:

01 - 29 on Munyon
30 - 56 on Myrtle

Data column from logger: (typical)

1 Pond depth
2 Delivery depth
3 Delivery backwater (elev)
4 Pond downstream (d/s) depth
5 Pond d/s flow

Year number: e.g., 5 for 1985

Month number: e.g., 08 for August
(could use week number)

Example: MY051608

MY - Myrtle lateral
05 - Logger 5
1 - data from first column
6 - 1986
08 - August

TITLE: FLOW MEASUREMENT AND CONTROL STRUCTURES

SPC: 1.3.03.1.f CRIS WORK UNIT: 5422-20740-013

FLUMES

The FORTRAN program on flume calibrations has been adapted to micro-computers and has received wide distribution. Dozens of diskettes have been mailed out to potential users of the program.

The flume program has been adjusted to produce a statistically fit, modified power-function equation that satisfactorily reproduces a computed flume table so it can be conveniently used in other computer programs for flow-depth conversions to discharge. The equation will reproduce the table values usually to within about 1%. A brute force trial and error approach was taken toward finding coefficients for the three parameter equation which is a modified power function. The method works well, but is slow on the slower micro-computers. A more elaborate search procedure could be developed.

Laboratory Work

Laboratory work was performed on the rectangular weir in the large glass flume. Attempts were made to reproduce data from the 1983 experiments. It was found, that very precise controls and measurements are needed to produce good results. Minor errors in measurement can have a significant effect on computed modular limits. Only a few successful runs were made. These tests were not completed in desired detail and are planned for extension. These preliminary results are given in Table 1.

Technology Transfer

Technology transfer activities included participation in a flow metering workshop conducted by the SCS and one sponsored by the NW Region of ASAE. About 50 design reviews and direct assistance in design of flumes was made for SCS, USBR, BIA, engineering consulting firms, cities, and irrigation districts.

The Long-Throated Flumes/Broad Crested Weirs are being installed in the USA and worldwide in large numbers. USAID India reports informally that "hundreds, maybe thousands" have been installed by Irrigation Projects in seven Indian states. Six flumes, with capacities ranging from 100 to 600 cfs were designed as a University of Idaho Masters Degree Project with only minor supervision from us. The project included studies of their construction conformity to the plans and current-metering of the flows to evaluate their field accuracy. The flumes performed as predicted with effects of submergence showing as predicted on two flumes that were constructed with sills nearly one foot lower than the plans specified. In both cases the deviation was dictated by the field construction managers with no consultations with the designers. These results and the evaluation of two Salt River devices of 2000 cfs capacity, illustrate that technology transfer is being accomplished after a fashion, but that the simplicity of the devices seems to encourage construction personnel

to declare unwarranted field changes. These preliminary reports and data are to be combined into a technical publication between our Laboratory, the University of Idaho, and the Salt River Project.

A large complex flume was constructed by a consulting firm in Colorado. They are now actively promoting flume construction. The complex shape was needed to measure high irrigation flows in the summer and low domestic flows in the winter. The structure replaced a Parshall Flume.

Publications Related to Flumes

An ARS publication on the use of the program has finally cleared ARS editing and is in press and should be available in early 1987. This is a full two years after it was submitted to the ARS publications branch. To speed up the process, we had prepared it in camera-ready text and tables for paste-up.

A number of other flume manuscripts are also in progress. The technical note on contraction ratios for flume designs was accepted by ASCE's Journal of Irrigation and Drainage Engineering. This method provides a means for conveniently fitting a flume to existing channel geometric shapes and hydraulic conditions.

The Technomics Civil Engineering Handbook chapter should be published some time in 1987. The Handbook will cover five volumes, with our chapter in the second volume under hydraulics.

The manuscript to quantify the effects of non-levelness of flume installations has been accepted by ASCE for publication. It basically showed why sloping a flume upward in the direction of flow causes less calibration shift than down-slope. Three-percent up-slope causes about 5% error if the flow is detected on a translocated stilling well. The corresponding down-slope error would exceed 10%. Detecting either reading on a fixed sidewall gauge would cause errors approaching 30%.

FLOW CONTROLLER

As previously reported, existing structures for the control of water levels and flow rates in canals have limitations in certain operational settings. Automatically controlled motorized gates are subject to the problems of power outages. They require limit switches and a control deadband which frequently makes them too imprecise for flow control into distribution-sized (lateral) canals. Float balanced gates are limited since the controlled level usually must be permanently fixed, or cannot be adjusted easily, and is usually not precise enough for flow rate control. Other schemes, such as the Danaidean controlled leak systems, are similarly inaccurate for flow rate and level control. For lateral sized canals (10 to 100 cfs), existing techniques for flow rate control can at best provide a constant flow rate within 10%.

As reported earlier (1986), we developed a new gate and outlet controller that requires no electrical power, is highly accurate and requires no artificial feedback delay beyond that inherent in the system components. Efforts are toward developing practical methods for retrofitting these controls to existing canal and reservoir outlet structures.

The DACL control system, used with a flume on the University of Arizona, Maricopa Agricultural Center (MAC) farm, was operated through 1986 with reasonable success. The shutter valve outlet was too small (12-inches square at the end of a 16-inch pipe) and caused too much head loss, making it difficult to get water at low operating heads. Fifty-five gallon drums were used for the control mechanism and float chamber. The control mechanism worked at the higher operating heads, but ,of course could not deliver the called-for flow at low heads. Attempts were made to improve the control settings, and it was found that care had to be taken in setting the valve overlap to assure proper control. Tying the two floats together with a common larger float as a field expediency with the hope of improving control is not advisable since this limits their separate functioning, which is needed when rapid changed are warranted. The system at the MAC farms was removed when the reservoir was expanded and the reservoir outlet moved. No plans are currently being made to reinstall this version of the system. The new designs discussed below may be installed.

An installation was nearly completed at the Ralph Wong farm in Marana, AZ. The outlet was a 24 inch pipe fitted with a 24-inch square shutter valve. The outlet channel was four feet wide. Two four-foot square, block-wall chambers were used for the stilling well control mechanism and for the float chamber. As of June, 1986, our portion of the installation of the mechanism was completed. The cooperator still had to install the manual outlet gate at the upstream end of the pipe, finish the canal wall where the rectangular outlet channel meets the trapezoidal slip form canal, and provilde a supply line from his well to the site. We will then tie the supply line into the pump. This work was interrupted by demands of the cropping season, and the cooperator chose to handle the flows manually, delaying the work until the end of the season. Completion and testing of this outlet is planned for 1987.

After constructing the reservoir outlet structure (12 cfs capacity) with one of the newly developed shutter valves on the cooperator's farm, it was decided to seek solutions that were even less complex in order to make these control systems more widely applicable and generally feasible, particularly for retrofit situations. New designs were conceived which combine the DACL controller with an expandible rubberized bag that can be of the material used in the Duke, Haise, and Payne (ARS, Fort Collins, CO) self-regulating reservoir outlet valve, which employs a bladder to regulate the outlet opening (Self Regulating Constant Discharge Valve, Journal of the Irrigation and Drainage Division, ASCE, Vol 103(IR2):275-278). The use of the valve controllers greatly increases the flexibility to retrofit the devices to a wide variety of outlet structures with minimum reconstruction, a problem with the Duke, et al., valving system. A possible limitation is the need for water pressures slightly greater than the pressure being controlled. This may require piping water from the next higher canal gate or the installation of an elevated tank and a small pump of some sort. A force plate or other force multiplying system can also be devised. Some work was completed on the construction of a portable DACL controller that can be applied to a wide variety of structures.

Monitoring and Examination of Water Level Control Structures

One of three controlled-leak Danaidean style structures on the Wellton Mohawk Irrigation and Drainage District was monitored for its ability to maintain a stable water surface. The data has not been fully reduced, but preliminary analysis confirms the $\pm$ 30 mm control band assumed. This would appear to be caused primarily by the wind effects on the skimming weir. When waves are present, the weir is fed by the wave tips and the control is then to this wave-tip level, thus lowering the average controlled water surface.

Twenty-six Danaidean style structures are operating in the Imperial Irrigation District. Some of them are not providing the expected control. The exact reason for the poor behavior was not determined. One controller on a radial gate that was 1.2 m wide was bypassing considerable water over the inflow funnel weir, which meant that the orifice valve was possibly large and wide open. The gate was in constant motion through a distance of about 50 mm and at a frequency of about 3 seconds.

We found an old Danaidean style control system on the San Carlos Irrigation and Drainage District. The system was designed to bypass storm flows into the east side of Picacho Reservoir, which is about one mile southeast of the intersection of Arizona State Routes 87 and 287, about 6 miles south of Coolidge. The gate is in the west side of the Canal. There are three radial gates about 4 m wide each, that are operated against common counterweighted wire-rope cables over pulleys. The 1.2-m diameter float appears to be made of concrete and is about 0.9-m deep. It is placed in a square concrete-lined tank that is 1.8 m on a side and is hydraulically connected to the canal The common counterweight operation means that the gates open when the float rises. It does not function well because more than a meter of sediments have deposited in the downstream outlet and sufficient water elevation difference to operate the float no longer exists. For this many gates, and small elevation differences, a large float on the order of 5 m diameter would be indicated. We were asked to make a recommendation on a remedy. Since electric power is near, we have recommended a pump-filled tank and a conversion to the DACL system.

An interesting aspect was that the operating personnel thought the device was original with the canal construction, or shortly after that. This would mean that this system may have been installed in the 1930s, which would seem too early, according to information from the French developers of this device type. Is it possible that these devices were independantly developed? No dated drawings have been located as yet.

Two Neyrtec float balanced types of gates were observed in California, one operated by an irrigation district, and one operated by a cooperate farm. Both seemed inappropriately applied. The District operated controller was to control downstream water levels from a falling-head reservoir source (Alsthom Atlantic, Inc. AVIO gate model). It was trying to maintain a constant level on an outlet gate located about a Km downstream. The friction slope for various flows was so different that the

downstream control level at the controller was required to vary by nearly 0.3 m. This was accomplished by the operating personnel using buckets of sand placed on the gate, thus reducing it to a semi-manual gate.

The other similar gate was in a long stretch of sloping canal. Its purpose was not apparent. It appeared to maintain a constant upstream canal level for ponding purposes only. Perhaps it allowed the rapid unannounced downstream shutdown of a user gate without overtopping the canal at the end of the reach.

Publications Associated with DACL Systems

Two manuscripts on the DACL systems have been accepted for publication. The results of the laboratory and field studies of the DACL control system will be published in a journal article to appear in ASCE Journal of Irrigation and Drainage Engineering (Feb. 1987). Another, describing canal controllers and their comparison to the DACL system, has been accepted for publication in Irrigation and Drainage Systems. A presentation before ASAE at their Summer meeting was well received.

FUTURE PLANS

The modular limit study will be completed. The methods proposed from these studies on visually estimating modular limits justify their need for publication.

A special handbook on the state-of-the-art in flow measurement for irrigation systems will be prepared.

Participation in one or two flow measurement workshops to fill the requests of other agencies (SCS, USBR, USAID, OICD) is expected. Construction of portable flumes with emphasis on ease of construction, economy, and field convenience will continue.

Test designs of flumes for sediment handling capability have been planned for laboratory verification of sediment passing capabilities. They are intended to lab-test the several proposed design concepts. (These tests are presently delayed for availability of technicians presently involved in starting new project.)

The reservoir outlet structure on the cooperator's farm will be: completed and tested. The new DACL-bladder system will be tested in the lab and in the field. We will continue to promote the new controller in applications in which it is retrofitted to existing canal works.

SUMMARY

Documentation of flume leveling effects, especially the quantification of these effects, allows the reliable application of the computer model to evaluate installation effects on any flume/weir of the long throated type. this will aid installers and construction inspectors to evaluate whether to accept a given construction or to require rebuilding.

The long-throated flumes are gaining wider acceptance and are gradually becoming the international standard device for canal flow measurements. They are also being used widely as the comparison standard when evaluating other devices because their calibrations can now be developed from well established physical principles with limited possibilities for error. Active participation in frequent design reviews and workshops, however, are still needed.

Effective, accurate, reliable and economical canal lateral controllers will allow main canal operators greater flexibility in passing variable flows down the canal without variations in outflows to the side-lateral openings. This in turn will allow inexpensive flow totalization at the farm outlets since constant deliveries can be totalized with simple timers.

Personnel: Replogle, J.A., Clemmens A.J.

Table 1. Comparison of 1983 lab tests, 1986 lab tests and computer predictions of modular limits.

	Modular Limits			
H1/L	computer	1983	1986	
6:1 ramp			second	first
0.1	0.795	0.772		
0.2	0.842	0.869		
0.3	0.869	0.925		
0.4	0.887	0.902		0.938
0.5	0.900	0.908	0.892	0.898
0.6	0.911	0.915	0.894	0.943
0.69	0.918	0.883	0.888	0.939
0:1 ramp				
0.1	0.672	0.663		
0.2	0.736	0.815		
0.3	0.778	0.800		
0.4		0.806		0.882
0.5		0.792	0.755	0.798
0.6		0.785	0.799	0.852
0.69		0.765	0.795	0.866

TITLE: SURFACE-DRAINING LEVEL FURROWS

SPC: 1.3.03.1.f CRIS WORK UNIT: 5422-20740-013

INTRODUCTION

Traditionally level basins, either flat planted or with furrows, are irrigated by turning a desired volume of water into the basin where it is confined until infiltrated. By configuring the water supply channel properly in relationship to the basin surface, some of the applied water can be drained from the inlet end of the basin after the irrigation advance is complete. Draining a portion of the applied water from the inlet end of the basin can potentially lead to lighter applications per irrigation and the applied water can be more uniformly applied than with non-draining basins. In many instances light applications are desirable to maintain high efficiencies (limited water holding capacity of sandy soils) and optimum soil, water, and air conditions for plant growth (low final intake rates on heavy clay soils can cause serious aeration problems).

The main difference between surface-drained level basins and conventional level basins is the way in which the water is conveyed and distributed to the basins. With conventional level basins, the water is turned into the basins from a canal or pipeline controlled with gates. With row or bed crops, secondary (temporary) ditches or channels are used to spread and divert water into the furrows. Once the required volume of water is applied to a basin, the gate is closed and the irrigation is complete.

In the surface-drained level-basin system, the canal not only conveys the water to the basin but is also used to spread and divert the water directly to the basin surface. The system consists of a series of terraced level basins. Each basin is irrigated separately by checking (or damming) the water in the channel or canal reach bordering the basin to be irrigated, Fig. 1. The channel is used only for conveyance when the water is not checked. When not checked, the water surface is below the basin surface or bottom of the furrow, Fig. 2.

The irrigation of the separate basins can proceed either in an upstream (basin 4 to basin 1, Fig. 1) or downstream (basin 1 to basin 4) direction. When irrigating in the upstream direction, the water applied to a basin remains on the basin until infiltrated. This is similar to the traditional way in which basins are irrigated in that all water introduced to a basin infiltrates into that basin. If, however, the irrigation progresses in a downstream direction, some of the water applied is drained back into the supply canal when the irrigation is changed to a lower-lying basin. It was this surface-draining process that is being studied.

The purpose of the project is to quantify the surface drainage phenomenon by a series of field studies. The studies will provide a data base for hydraulic model verification and guidelines for designing and managing such systems.

FIELD STUDY PROCEDURES

General

Procedures have been developed for evaluating the performance of furrow irrigation systems. The required measurements depend somewhat upon the objectives of a particular evaluation and to the resources available. The developed procedures provide for evaluating the distribution uniformity along the furrow but generally rely on infiltration characteristics of the soil to be developed from furrows adjacent to the test furrow. The infiltration measurement techniques include the use of blocked furrows, recirculating furrow infiltrometers, or inflow-outflow procedures. Many times such procedures provide satisfactory performance evaluation results.

The infiltration function can also be estimated from volume balance calculations where cumulative infiltrated volume at some time during advance in the test furrow is equated to the difference between the cumulative inflow volume and the surface storage volume at that time. The amount of water in surface storage is either calculated from sufficient furrow cross-section and water depth measurements or is estimated by an empirical relation between the inlet cross-sectional flow area, the advance distance, and a water surface shape factor.

For studies where a precise data base is needed, e.g. furrow hydraulic model verification, the accuracy of the analysis can be improved by measuring the water surface profile in the furrow throughout the irrigation or test. The approach requires accurate evaluation of the furrow hydraulics which necessitates careful characterization of the furrow geometry, measurement of furrow inflow and outflow, and accurate measurement of the water surface profile in the furrow. A procedure has been developed to provide these data on an individual furrow basis. The procedures and equipment used differ from that used on conventional sloping furrows in that the water drained from the level furrow system studied was drained from the inlet end of the furrows, rather than the downstream end.

Inflow Control

Portable RBC flumes were used to measure the water delivered into individual furrows. Water was supplied to the flumes, through 38 mm lay-flat hose, from a submersible pump. To reduce turbulence in the flume, an entrance section to the flume was designed to dissipate inflow energy by utilizing a stilling baffle and flow straightening wings. Flow rate regulation was done manually with a ball valve attached to the entrance section and by observing a wall gauge mounted directly on the sidewall of the flume. The approximate required flow rate was set by observing the wall gauge and adjusting the valve. Exact flow rate and total volume of water delivered were determined by periodically checking the water surface with a point gauge. To minimize error in measurement the readings should be taken in a translocated stilling well located on a centerline of the flume and just downstream of the throat.

Furrow Water Storage Measurement

The water depth at selected stations (distances) along the furrow was recorded every three minutes, providing a hydrograph for each station, Fig. 3. These hydrographs provided both a tracing of the advancing water and, when combined from station to station at a selected time, defined the water surface profile. The furrow cross-section was defined at each station using a power function relating width to depth. By knowing the water depth at each station and the furrow cross-section the infiltrated water volume could be estimated each time the advancing front reached a measurement station (infiltrated volume obtained by subtracting surface storage from known volume applied).

Water level measurement: Water depth along the furrows was recorded automatically by adapting the double-bubbler/pressure transducer system developed here at the U.S. Water Conservation Laboratory. To adequately define the water surface profile during a test, bubblers were located at selected stations along the furrow (furrow inlet, 5, 10, 20, 30 m and at every 30 m thereafter).

A set of two reference bubblers (double-bubbler) was housed in a stilling well near the logger. Reference readings were taken from the double-bubbler and atmosphere at the beginning of each three minute sensing cycle to provide an up-to-date calibration of the pressure transducer. After the calibration readings were taken, the bubblers at each station along the furrow were scanned for recording the head. A 24-station scanning valve was used to switch from bubbler to bubbler. The scanning valve was controlled by either an expanded version of a HP41CV calculator (during 1984) or an Omnidata Easy Logger (during 1986). The stations were repeatedly scanned with the transducer voltages being stored on either cassette tapes (HP) or solid state data storage packs (EPROM--Easy Logger). The pressure at each bubbler was sampled for two seconds.

Compressed air, regulated to about 70 kPa (10 psi), was supplied by an air tube manifold common to all bubblers. The air can be supplied either from an air compressor, if available, or high pressured bottled air. In our case we used bottled air. Air flow to each bubbler was controlled to about two or three bubbles per second by a flow control valve located near the bubbler. The pressure at the bubbler was sensed with a plastic tube leading from the bubbler back to the scanning valve.

The furrow bubblers were mounted in furrow stilling well assemblies (cups constructing using 7.5 cm [3 in.] diameter PVC pipe capped on one end). Bubblers were constructed of copper tubing. Black polyethylene tubing (3.17 mm ID, 6.35 mm OD) was used between the scanning valve and the tee near the bubbler. The bubbler/stilling well assembly was buried slightly below the furrow bottom at the various sites to be sensed along the furrow. Water depth in the furrow can then be calculated from the head sensed by the logging system in conjunction with field-surveying the furrow bottom relative to the top of the buried cup. The position of the bubbler relative to the top of the cup was determined in the laboratory.

Furrow cross-section measurement: Furrow cross-sections were quantified by recording the furrow cross-sectional profile, measuring down from a level reference reaching across the furrow. These data were then used to characterize the cross-section by relating water depth to furrow width using a power function. Measurements are taken at each station where the water depth is being sensed, both before and after the irrigation. The after irrigation cross-sections are used for furrow storage volume calculations.

Outflow Measurement

A specially designed portable flume was constructed to measure the flow of water as it drains back out of a test furrow. Measuring surface drainage directly provides a volume balance check on the furrow during the drainage stage. The flume used to measure the drainage was designed so that the flume was nonrestricting to the drainage process, e.g., outlet of the furrow must be free-draining. A complex shaped flume which consisted of a V-shaped section inside a rectangular section was used to form the flume throat. Such a shape (V-section 1 vertical: 2.5 horizontal) provided accurate measurement at low flows (a large portion of the drainage was at low flow rates) and approximated the furrow cross-section. To simulate natural drainage from the furrow the crest of the flume was set at the same elevation or slightly below the bottom of the furrow. In this way the flume was nonrestricting to flow and the drop through critical as the water exited the flume defined the end of the furrow.

The flume was equipped with a drop gate at the exit to serve as a closure to the inlet of the furrow during the advance phase of the irrigation. Drainage was initiated by opening the gate. Water tightness was maintained by lining the gate with rubber sheeting.

The water surface elevation in the flume was read manually during the initial stages of the drainage process to supplement the automatically logged elevations (logged on three minute intervals). The supplemental data points were obtained from point gauge readings taken about every 10 to 15 seconds in a stilling well located on the centerline of the weir. These same flumes, although designed for studying surface water drainage back out of level furrows, could be used as well to measure runoff from sloping furrows.

TESTS CONDUCTED IN 1986

A test site was established at the University of Arizona's Maricopa Agricultural Center on their field plot number 11. The field was precisely leveled by the University using their laser-controlled scraper. The standard deviation of the field elevations taken over the finished area (60 m x 360 m) used for the level furrow study was 6.0 mm, which is considerably better than most "precisely" leveled basins. The area was furrowed out immediately after leveling, establishing relatively deep furrows on 1.02 m (40 inch) centers. Once the test furrows were established, a drainage channel to be used to hold the drainback from the

level furrows, was constructed across the end of the furrows. The maximum working length of the test furrows was 354 m after the drain channel was established and space was allowed for the test trailer.

A series of 18 furrows were selected for test purposes; 6 each at 120 m, 240 m, and 354 m long. Each furrow was "irrigated" three times--Dry (soil moisture conditions as they were found at the time of the test), Wet 1 (2 days after the first test), and Wet 2 (about one week after the Wet 1 test). No crop was being grown on the plots. Three identical sets of monitoring equipment had been developed so three furrows were evaluated at the same time (any one day). Any daily test would include 1 furrow from each of the 3 lengths. The tests conducted differed only in inflow rate, criteria for inflow cutoff, and whether or not surface drainage was allowed. The specific setup conditions follow:

Setup #1: Inflow rate: 4 l/s.
Inflow cutoff: When advancing water reached end of furrow.
Surface drainage: Yes, immediately after inflow stopped.

Setup #2: Same as Setup #1.

Setup #3: Inflow rate: 3 l/s (long furrow shortened to 300 m due to slow advance time).
Inflow cutoff: When advancing water reached end of furrow.
Surface drainage: Yes, immediately after inflow stopped.

Setup #4: Inflow rate: 4 l/s.
Inflow cutoff: 120 m furrow--10 minutes after advancing water reached end of furrow.
240 m furrow--20 minutes after advancing water reached end of furrow.
354 m furrow--30 minutes after advancing water reached end of furrow.
Surface drainage: Yes, immediately after inflow stopped.

Setup #5: Same as Setup #4.

Setup #6: Inflow rate: 4 l/s.
Inflow cutoff: When advancing water reached end of furrow.
Surface drainage: None.

Water was available from a nearby well. Inflow to each furrow was provided by the submersible pumps, described earlier, from ponded water in a concrete lined canal located along the inlet end of the furrows.

DATA ANALYSIS

Computer programs are being developed to analyze the field data. The first program, with an original version (KRUNCH) finished in 1985, provides the main data reduction and is being redone (CRUSH) to accept input from the Easy Logger. This program uses 6 input files:

XDIS: Distances to monitoring stations along furrow.

VLT***[1]: Transducer output voltages from the Easy Logger for atmosphere, the reference double-bubblers, outlet flume, and the bubblers from each furrow station.

HPF***: Elevation readings for each furrow--5 rod readings at each station, 4 of the bottom of the furrow near each station and 1 on the top of the bubbler cup.

FLM***: General description of test, clock synchronization (watches and Easy Logger), outflow flume calibration check, and point gauge readings on both the inflow and outflow flumes.

XSA***: Furrow cross-section measurements at each station for each furrow.

TARE: Distance of bubbler below top of cup for all cups used in the study.

Output files from this program includes:

1. Water depth and time (hydrograph) for each station.
2. Flow rate data (inflow vs. time and outflow vs. time).
3. Furrow cross-sectional characteristics for each station. This includes best-fit power function terms for both furrow width vs. depth and wetted perimeter vs. depth.

The second program (PROFL) will use as output from KRUNCH or CRUSH. Along with summarizing the test results by station, the water surface profile is also computed for the furrow each time the advancing water reaches a test station. Output from this program is stored in file FPR***.

The third program will use the FPR*** file to develop the infiltration parameters using the previously described volume balance approach.

Other items to be studied will include:

1) Quantify the volume of water that can be drained from a level furrow relative to the furrow length and infiltration characteristics.

2) Relate the gross water applied to net water infiltrated.

3) Evaluate the application uniformity for each irrigation.

4) Evaluate the capability of the bubbler system (accuracy and response relative to distance from the logger).

[1]***Refers to test number.

These field data will be used to verify the recently developed zero-inertia furrow model. Once the model is satisfactorily verified the model will then be used to develop design and operation guidelines for the use of surface-draining level furrows.

OTHER APPLICATIONS OF THE WATER LEVEL SENSING EQUIPMENT

Multiple water surfaces, even though located some distance apart, can be measured with the bubbler/pressure transducer system at a central logging site. The bubbler method, in addition to the water level measurements in furrows reported herein, is currently being used in the following ways at the U.S. Water Conservation Laboratory:

1) The original bubbler/pressure transducer method was used to monitor water being delivered to individual farms. The system was controlled by a hand-held programmable calculator (HP41CV) and the data were stored on a cassette tape. This same system configuration is presently used to measure and record individual irrigation deliveries to basins on which crop production variability is being studied.

2) A monitoring system developed to study water levels in an Irrigation District canal and deliveries to individual farms features the double-bubbler/pressure transducer method. In this research study water levels are monitored on a 15 minute interval at each farm turnout and/or check gate located along the canal. Thirteen logging sites are being used, with anywhere from one to seven water surfaces being measured at any one site. The maximum distance from the logger-controller to where a bubbler is location is about 40 m. The system features an Easy Logger and three-way solenoid valves for switching from bubbler to bubbler. Air is supplied by a dc-powered instrument pump. The equipment cost per water level measurement (three water levels per site) averaged between $800 and $900 depending on the amount of data storage needed at a site. This cost is considerably less than for any other means available.

3) The bubbler system is being used to evaluate infiltration variability in flooded irrigated basins. The falling head, within infiltrometer rings, was measured using bubblers. Measurements were made about every two minutes from the time water was introduced until totally infiltrated. Rings were located on borders as long as 300 m. A Polycorder (Omnidata) was used for control and logging. A scanning valve was used to switch from bubbler to bubbler.

4) The bubbler method was used on a flowing furrow infiltrometer developed cooperatively with the Soil Conservation Service. The falling water surface within tanks used to supply water to the study furrow, was measured and recorded. This rate of fall was representative of the infiltration rate and the amount of drop represented the cumulative infiltration at any time during the text. The system was controlled using and HP41CV, with the data stored on a cassette tape.

SUMMARY

Draining a portion of the applied water from the inlet end of a level furrow can potentially lead to lighter applications per irrigation and the applied water can possibly be more uniformly applied than with non-draining basins. In many instances light applications are desirable to maintain high efficiencies (limited water holding capacity of sandy soils) and optimum soil, water, and air conditions for plant growth (low final intake rates on heavy clay soils can cause serious aeration problems). A field study is underway to quantify this surface drainage phenomenon from level furrows. The studies will provide a data base for hydraulic model verification and guidelines for designing and managing these systems. Eighteen furrows were individually irrigated, three different times, for a total of 54 tests during 1986 and early 1987. The characteristics of each furrow and each irrigation (advance, recession, water depth at selected sites along a furrow, furrow cross-section, etc.) were precisely measured. Factors that were varied from test to test included furrow length, inflow rate, gross water applied, antecedent soil water, and drained and non-drained conditions. Data reduction programs are being developed which will allow analyses of infiltration, water surface profiles, advance, recession, water drained from the furrow, distribution of the amount of water drained along the furrow, and final irrigation uniformity.

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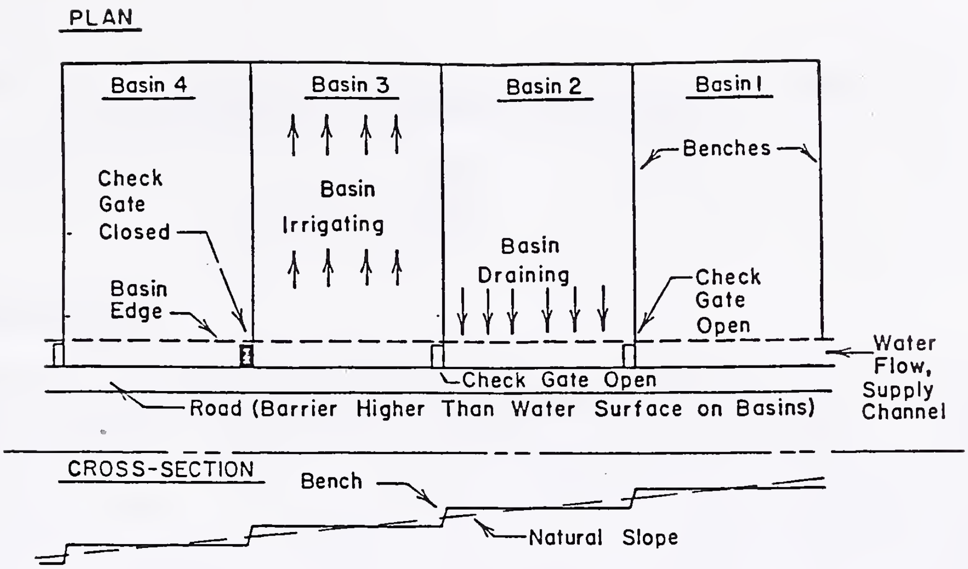

Fig. 1. Plan and cross-sectional views of level basins (benched) irrigated from an unlined channel. The irrigation has just been changed from basin 2 to basin 3 (downstream).

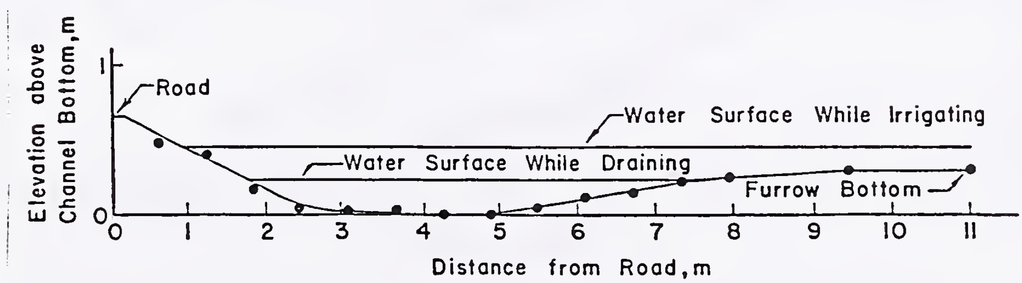

Fig. 2. Cross-sectional view of unlined supply channel from field road to level basin. Water surfaces shown were those recorded during an irrigation with the maximum depth reaching about 15 cm (6 in.). Note that the vertical and horizontal scales are not the same.

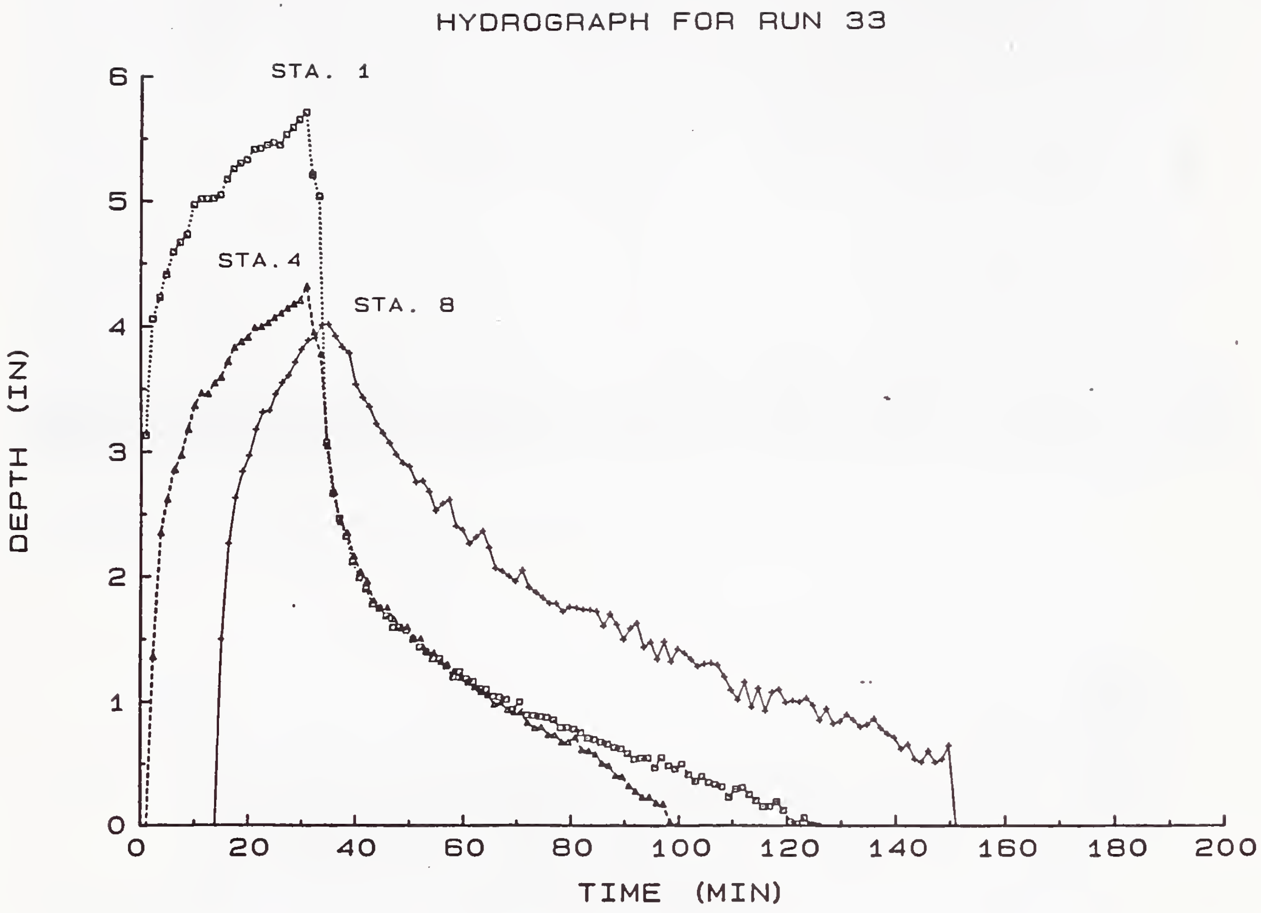

Fig. 3. Hydrographs developed for three stations along a test furrow. The water depth readings resulted from the pressure transducer voltage readings taken at each station and later converted to depth values taking into account the depth of the bubblers relative to the bottom of the furrow.

TITLE: PLANT WATER RELATIONS, PHOTOSYNTHESIS, AND RUBBER CONTENT OF YOUNG GUAYULE PLANTS DURING WATER STRESS

STRATEGIC PLAN: 2.3.04.1.n 20% CRIS WORK UNIT: 5422-20740-014
1.3.03.1.d 80%

INTRODUCTION

Guayule (Parthenium argentatum Gray) is a xerophytic, rubber-producing shrub native to Texas and northern Mexico. Its leaves are densely covered with multicellular trichomes and a hard wax which reduce water loss from the leaves (Ray, 1983). Guayule also has an extreme tolerance of desiccation. Plants have been observed to recover rapidly from a relative leaf water content as low as 30% (Ehrler et al., 1985 and Ehrler and Nakayama, 1984). Little else is known, however, about the drought tolerance or plant water status of guayule during drought. Understanding the natural processes involved in the control of plant water status can be valuable in formulating plans for breeding and management (Jones et al., 1985).

Knowledge regarding the water relations of guayule is of particular importance since guayule rubber yield is affected in two opposing ways by soil moisture stress. Bucks et al. (1985b) showed that guayule dry matter, rubber, and resin yields were linearly related to amount of applied water, with the greatest amount of irrigation water producing the highest yields. They also found that water use of guayule was higher than many former estimates for an arid zone crop (Bucks et al., 1985a) in spite of the fact that guayule survives under natural conditions in the arid southwest on only 175 to 380 mm of rainfall per year (Ray, 1983).

Other studies have shown that water stress causes guayule plants to accumulate a larger percentage of rubber in its stems and roots (Retzer and Mogen, 1947; Veihmeyer and Hendrickson, 1961; Hammond and Polhamus, 1965; and Mondrus-Engle and Younger, 1983). This inverse relationship between plant growth and percent rubber has been observed previously (Hunter and Kelley, 1946) and suggests that a better understanding of how plant water status affects rubber production may provide crucial information for future breeding and management of guayule.

The objective of this study was to observe selected physiological characteristics related to plant water status in order to gain a better understanding of the mechanisms which control drought tolerance in guayule, and to investigate the relationship between plant water status, plant growth and rubber production during a prolonged drought period.

MATERIALS AND METHODS

Seedling Establishment

Approximately 300 guayule seedlings (cv N565 II) were propagated in a glasshouse from seeds planted during January 1986 in 1:1 (v:v) medium-grained vermiculite and Sunshine Mix No. 2 (Fisons Western Corp., Vancouver, B. C., Canada[1]) media in 50 by 74 mm speedling trays (Speedling Mfg., Inc., Sun City, FL). The plants were placed under misters which operated for approximately 2 min twice a day and were watered twice each week with full strength Peters Hydro-sol nutrient solution (Peters Fertilizer Products, Fogelsvill, PA).

Field Site and Irrigation Treatment

The field site was located at the U. S. Water Conservation Laboratory in Phoenix, AZ, on an Avondale loam soil (a fine, loamy, mixed calcareous, hyperthermic, Antropic Torrifluvent). Prior to planting, the soil was ripped to a depth of 450 mm, tilled, leveled, and fertilized with 57 kg ha^{-1} N as $Ca(NO_3)_2$. The site was divided into four 3 by 5 m plots. A 2.4 m deep steel neutron probe access tube was placed in the center of each plot. The four plots represented two replications of two irrigation treatments in a randomized complete block design.

The seedlings were transplanted into beds in the field plots on the 87th day of the year (DOY). Each plot consisted of 5 beds with 8 plants per bed. Bed spacing and plant spacing within beds was 600 mm. All plots were flood irrigated immediately after transplanting. A microirrigation system (T-tape type C, T-Systems, Corp., San Diego, CA) was installed on DOY 92 and used for all subsequent irrigations. All plots received weekly irrigations of equal amount through DOY 148 in order to insure equal establishment of the seedlings.

The two irrigation treatments were a well-watered or nonstress treatment and a stress treatment. The nonstressed plots received subsequent irrigations at approximately 20 to 30% depletion of the available soil moisture in the root zone (about every 10 days). The stress plots were not irrigated again until DOY 217 when soil moisture had reached the wilting point (0% available soil moisture). A neutron probe (model 503, Campbell Pacific Nuclear Corp., Pacheco, CA), previously calibrated in the same soil type, was used to estimate soil moisture content two to three times per week beginning DOY 149. Physiological measurements were conducted between 1000 and 1045 hr MST two to three times per week beginning DOY 149 (29 May) and ending on DOY 228 (16 August). Measurements were taken only on clear days.

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[1] Trade names and company names are included for the benefit of the reader and do not imply endorsement by the U.S. Department of Agriculture.

Net Photosynthesis Measurements

Net photosynthesis (Pn) was measured on one plant per plot as follows. Two 5mm thick by 400 mm diam neoprene disks, each with a slit cut from edge to center, were slid underneath the plant, with the slits offset, forming an effective gas exchange barrier between the plant and soil. A cylindrical transparent lexan assimilation chamber was placed over the plant and pressed firmly against the neoprene disks, forming an airtight seal. A 7.7 L chamber (275 mm high by 190 mm diam) was used at the beginning of the experiment and a 20.8 L chamber (380 mm high by 310 mm diam) was later used as the plants became larger. The air in the small and large chambers was mixed with one or two 45 mm diam 12 v fans, respectively.

Two 8 cm^3 gas samples were extracted by syringe from the chamber, the initial 5 s after the chamber was set in place and the final at 15 s for the small chamber or 30 s for the large chamber. The CO_2 concentration in the syringes was measured with an infrared gas analyzer (model 225-MKB, Analytical Development Co., Ltd., Hoddesdon, England). The difference in CO_2 concentration was used to calculate the photosynthetic rate. The analytical procedure closely followed that of Clegg et al. (1978).

Pn was measured on the same plants for a two week period. The plants were then harvested and leaf areas estimated with an area meter (model 3100, Li Cor, Inc., Lincoln, NE) for use in calculating Pn on a leaf area basis (μMol CO_2 m^{-2} s^{-1}). The roots and stems of the harvested plants were then analyzed for rubber and resin content according to a previously described gravimetric procedure (Black et al., 1983).

Water Potential Measurements

Two other plants per plot were sampled for psychrometric measurement of water potential (Ψ_L) and osmotic potential (Ψ_S). A single fully expanded leaf located near the top of the canopy was excised at the petiole from each plant and immediately sealed in a Wescor model C-30 chamber equipped with a model PST-55 thermocouple psychrometer (Wescor, Inc., Logan, UT). Thermocouple psychrometers were calibrated against known NaCl solutions prior to the experiment. The samples were taken to a constant temperature room (25 ± 1 C) and placed into a foam rubber block that was contained in an insulated cooler.

Ψ_L measurements were conducted after a 4 to 5 hr equilibration period using a microvoltmeter (model HR 33-T, Wescor, Inc., Logan, UT). The samples, still in the psychrometer chambers, were then immersed in liquid nitrogen for approximately 3 min to rupture cell membranes (Walker et al., 1983). After the frozen samples warmed to room temperature they were placed back into the insulated cooler and allowed to equilibrate for another 4 to 5 hr, after which Ψ_S was measured. Pressure potential (Ψ_P) was calculated as $\Psi_P - \Psi_S$.

Canopy Temperature, Transpiration, and Conductance Measurements

Canopy temperatures (Tc) of 12 plants per plot were measured with an infrared thermometer (model 110, Everest Interscience, Tustin, CA). Transpiration (Tr) and stomatal conductance to water vapor (Cs) were measured on abaxial surfaces of three leaves on three different plants per plot with a steady state diffusion resistance porometer (model 1600, Li Cor, Inc., Lincoln, NE). Adaxial leaf surfaces were found to behave similarly, but were not routinely measured because of difficulty encountered securing the small guayule leaves in the sensor head leaf clamp.

Statistical Analysis

Mean values for all parameters in each plot were used in calculating a repeated measures analysis of variance with the irrigation treatments as whole plots and the 30 days on which measurements were conducted as subplots. Standard errors shown in the legends of figures 2 through 4 were calculated according to Steel and Torrie (1980), and represent the standard error (SE) of the difference between any two means for that parameter.

RESULTS AND DISCUSSION

Irrigation water was withheld from the stressed treatment for 70 days during which only 27 mm of rain were received. During this same period the nonstressed treatment received six additional irrigations of approximately 100 mm per application, bringing the soil moisture content up to "field capacity" each time and represented as 100% available soil moisture in Fig. 1.

Measurable differences of most physiological responses to soil moisture depletion between the stressed and nonstressed treatment were not apparent until approximately 20 to 30 days after the last irrigation of the stressed treatment. At this time 65 to 70% soil moisture depletion had occurred in the root zone of the stress treatment. Differences in Tr, Cs, and Tc (Fig. 2, 3, and 4, respectively) between the two treatments gradually increased until 57 days into the stress treatment (DOY 205). Between DOY 205 and the end of the stress period Tr and Cs of the stressed plants declined rapidly to values less than one-half those of the nonstressed plants and Tc increased sharply. During this same period the soil moisture content in the stressed plots reached the wilting point value of 0% available soil moisture (Fig. 1).

Soil moisture content was not significantly correlated with Tr, Cs, or Tc in either treatment, indicating that these parameters were probably more sensitive to the instantaneous evaporative demand than soil moisture stress. Tr, Cs, and Tc of the stressed plants were, however, significantly correlated with Ψ_L (Table 1).

The stressed plots were irrigated on DOY 217 to alleviate stress. Soil moisture content up to field capacity was attained. During the 11 day period following irrigation, however, the stressed plants recovered

only partially, as compared to the nonstressed plants. Tr (Fig. 2) and Cs (Fig. 3) of the stressed plants remained significantly lower and Tc (Fig. 4) significantly higher than the nonstressed plants.

A similar response to soil moisture depletion was observed for Ψ_L and Ψ_S measurements (Fig. 5). Ψ_L and Ψ_S of the stressed plants declined gradually compared to the nonstressed plants until soil moisture content neared the wilting point. Ψ_L and Ψ_S then dropped more rapidly to values approximately 1.5 MPa lower than the nonstressed plants. Ψ_P values of stressed and nonstressed plants did not differ, however, until soil moisture in the stressed plots reached the wilting point, when Ψ_P of the stressed plants dropped below 0.0 MPa. Recovery of Ψ_P following the DOY 217 irrigation of the stressed plants was complete within 24 hr. Ψ_L and Ψ_S of the stressed plants, however, remained below the nonstressed plants during the 11 day period following irrigation (Fig. 5).

Ehrler and Nakayama (1984) and Ehrler et al. (1985) observed that guayule recovers rapidly from stress based on relative leaf water content measurements. Based on Tr, Cs, Tc, Ψ_L, and Ψ_S measurements of the stressed plants in this investigation, recovery to levels of the nonstressed plants did not occur within 11 days following irrigation. Ψ_P measurements, which are more closely associated with relative leaf water content than other plant water status parameters (Jones et al., 1985), did respond with a rapid recovery upon irrigation.

Pn of both the stressed and nonstressed plants declined by greater than 50% between the beginning and the end of the experiment (Fig. 6). A slight increase in Ta over the course of the experiment may be partially responsible for this behavior. Pn of stressed and nonstressed plots were both negatively correlated ($P<0.01$) with Ta (Table 1). Pn in both treatments was also significantly correlated ($P<0.01$) with their corresponding Ψ_L and Ψ_S (Table 1). In addition, the plants became larger over the course of the study (Table 2), such that a larger proportion of leaves became shaded by the new growth as the experiment progressed. These three factors may all have played a role in the apparent decline in photosynthesis.

Pn of the stressed and nonstressed plants declined similarly until about the fourth week of the stressed treatment. Pn of the nonstressed treatment then began to decline at a faster rate than the stressed treatment until approximately DOY 200 (a period of 30 days). On several days during this period, the Pn rates of the stressed plants were significantly higher than the nonstressed plants. Beyond DOY 200, when soil moisture in the stressed plots approached the wilting point, the Pn rates of stressed plants declined to levels similar to the nonstressed plants. Pn values of the stressed plants during the 11 day period after irrigation on DOY 217 were all lower than the nonstressed plants, though the differences were not statistically significant.

The osmotic adjustment and corresponding turgor maintenance in the stressed plants was probably responsible for maintaining Pn similar to the nonstressed plants even though large differences in Ψ_L occurred.

Jones (1973) and Kaiser (1982) have shown that Pn is more closely related to Ψ_P than other parameters related to plant water status such as Ψ_L or Ψ_S.

A possible explanation for the apparently higher Pn rate of the stressed plants during the middle portion of the stress period is that the specific leaf weight (SLW) of the stressed plants progressively increased during the stress period when compared to the nonstressed plants. The means for SLW of the stressed and nonstressed plants on DOY 214, the last harvest before the final irrigation of the stressed plants, were 105.1 ± 5.1 and 86.7 ± 3.8 g m^{-2}, respectively, on a dry weight basis. This 21% higher SLW for the stressed plants, accompanied by a noticeable (but not measured) increase in leaf thickness, probably resulted in a greater photosynthetic capacity per unit leaf area.

Pn rates of 8 to 10 μMol m^{-1} s^{-1} observed at the beginning of the experiment were similar to those reported for some other arid zone species (Nobel et al., 1978; Seeman et al., 1984; and Wardlaw et al., 1983). The continual decline of Pn over the course of the experiment, however, indicates that Pn was probably at a higher rate earlier in the spring. This assumption is supported by the observed growth rates of guayule in Arizona which are highest in the spring and fall and lowest during the summer (Bucks et al., 1985c).

Even though the stressed plants had a slightly higher average Pn rate than the nonstressed plants and they maintained positive Ψ_P through osmotic adjustment, their growth during the stress period was significantly less ($P<0.05$) than the nonstressed plants. The average fresh weight of the stressed plants was 39% less than the nonstressed plants by the end of the stress period on DOY 214 (Table 2).

This result indicates that a substantial amount of the carbon fixed by the stressed plants was diverted to uses other than plant growth. One carbon sink in guayule is rubber synthesis. The percent rubber in both treatments progressively increased throughout the experiment. The increase is much more evident in the stressed plants, however, which showed more than a 5-fold increase in percent rubber, whereas rubber content of the nonstressed plants doubled over the same period (Table 2). Resin content, in contrast, was not significantly influenced by the moisture stress treatment. The higher rubber content of the stressed plants would require the diversion of proportionately more carbon from growth and development to rubber synthesis. However, the small percentages of rubber found in these plants are probably not entirely responsible for the large differences in growth that were observed.

Another possible carbon sink is osmotic adjustment. Osmotic adjustment to water stress in other species has been associated with reductions in growth and development which may indicate greater carbon allocation to alleviate water stress through synthesis and accumulation of organic solutes (Henson, 1985; Hitz et al., 1982; and Meyer and Boyer, 1981). A significant level of osmotic adjustment was attained by the stressed guayule. P_L of the stressed plants was as much as 1.2 MPa lower than

the nonstressed plants while maintaining a similar Ψ_P (Fig. 5). No studies have yet been conducted to determine the nature of the osmoticum or the energy requirements for osmotic adjustment of guayule.

The results of this study indicate that leaf osmotic adjustment and the resulting maintenance of positive Ψ_P play an important role in the drought tolerance of guayule. Further research is required to discover the nature of the accumulated solutes. The metabolic cost of osmotic adjustment appears to be substantial, however, as plant growth was reduced by 39% during the 70 drought period. It was also demonstrated that Pn of guayule declines to very low levels during the summer months, regardless of soil moisture content. The reason for the decline in Pn is not completely understood, although high temperatures may be involved. The decline in Pn was not related to Cs, however, which remained at relatively high levels for the nonstressed plants. Rubber synthesis of the stressed guayule was over 2.5 times greater than the nonstressed plants. This result indicates that controlled periods of stress may have potential as a management technique to increase rubber content as well as reduce irrigation requirements. The benefits of increased rubber content and reduced water use would have to be carefully balanced against concurrent reductions in biomass to achieve an optimum economic return.

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PERSONNEL

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Table 1. Correlation coefficients for environmental and physiological parameters measured on stressed (S) and nonstressed (N) guayule between 29 May (DOY 149) and 16 August (DOY 218) 1986.

Parameter		Air Temper-ature	Soil Moisture Content	Net Photo-synthesis	Tran-spiration	Stomatal Conduc-tance	Canopy Temper-ature	Water Potential	Osmotic Potential
Soil Moisture Content	N	.07							
	S	-.08							
Net Photosynthesis	N	-.49**	.05						
	S	-.56**	.37*						
Tranpiration	N	.12	-.19	-.45*					
	S	-.42*	-.04	.43*					
Stomatal Conductance	N	.05	-.16	-.55**	.83**				
	S	-.52**	.16	.38*	.85**				
Canopy Temperature	N	.58**	-.30	-.34	-.37	-.43*			
	S	.75**	-.20	-.72**	-.80**	-.74**			
Water Potential	N	-.72**	.14	.57**	-.28	-.22	-.73**		
	S	-.56**	.73**	.78**	.42*	.51**	-.84**		
Osmotic Potential	N	-.62**	-.14	.51**	.23	-.10	-.45*	.63**	
	S	-.55**	.56**	.81**	.56**	.54**	-.76**	.92**	
Pressure Potential	N	-.28	.28	.18	-.21	-.04	-.41*	.60**	-.19
	S	-.41*	.55**	.20	.21	.33	-.45*	.61**	.27

*, ** Correlation coefficients significant at $P < .05$ and .01 level, respectively

Table 2. Rubber and resin content (as percent of dry weight) of water stressed (S) and nonstressed (N) guayule on four days during 1986.

		Harvest Date (Day of Year)			
		171	185	201	214
Extractable Soil Moisture %	N	101	83	94	80
	S	43	24	10	1
Rubber, %	N	0.4 ± 0.0a[t]	0.6 ± 0.0a	0.8 ± 0.1a	0.8 ± 0.3a
	S	0.4 ± 0.1a	0.6 ± 0.1a	1.7 ± 0.4b	2.1 ± 0.6b
Resin, %	N	4.8 ± 0.1a	4.6 ± 0.5a	3.7 ± 0.3a	3.7 ± 0.6a
	S	5.2 ± 0.4a	5.0 ± 0.2a	4.2 ± 0.4a	4.1 ± 0.5a

[t] Means followed by different letter are significantly different at .05 level.

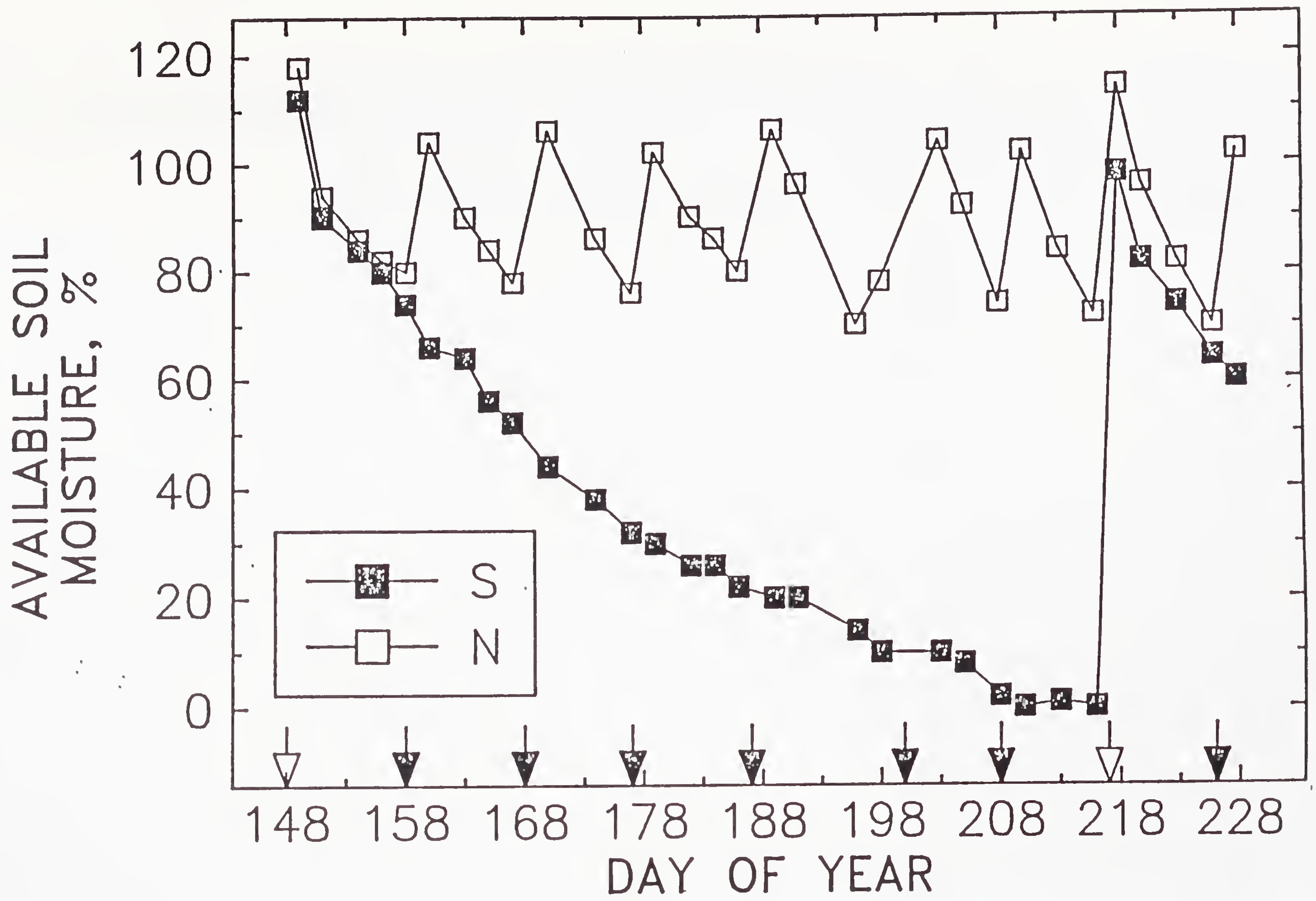

Figure 1. Percent of potential extractable soil moisture in the stress (S) and nonstress (N) treatments between DOY 149 (29 May 1986) and DOY 228 (16 August 1986). Solid and open arrows on the abscissa refer to days when the nonstressed or both the nonstressed and stressed treatments were irrigated, respectively.

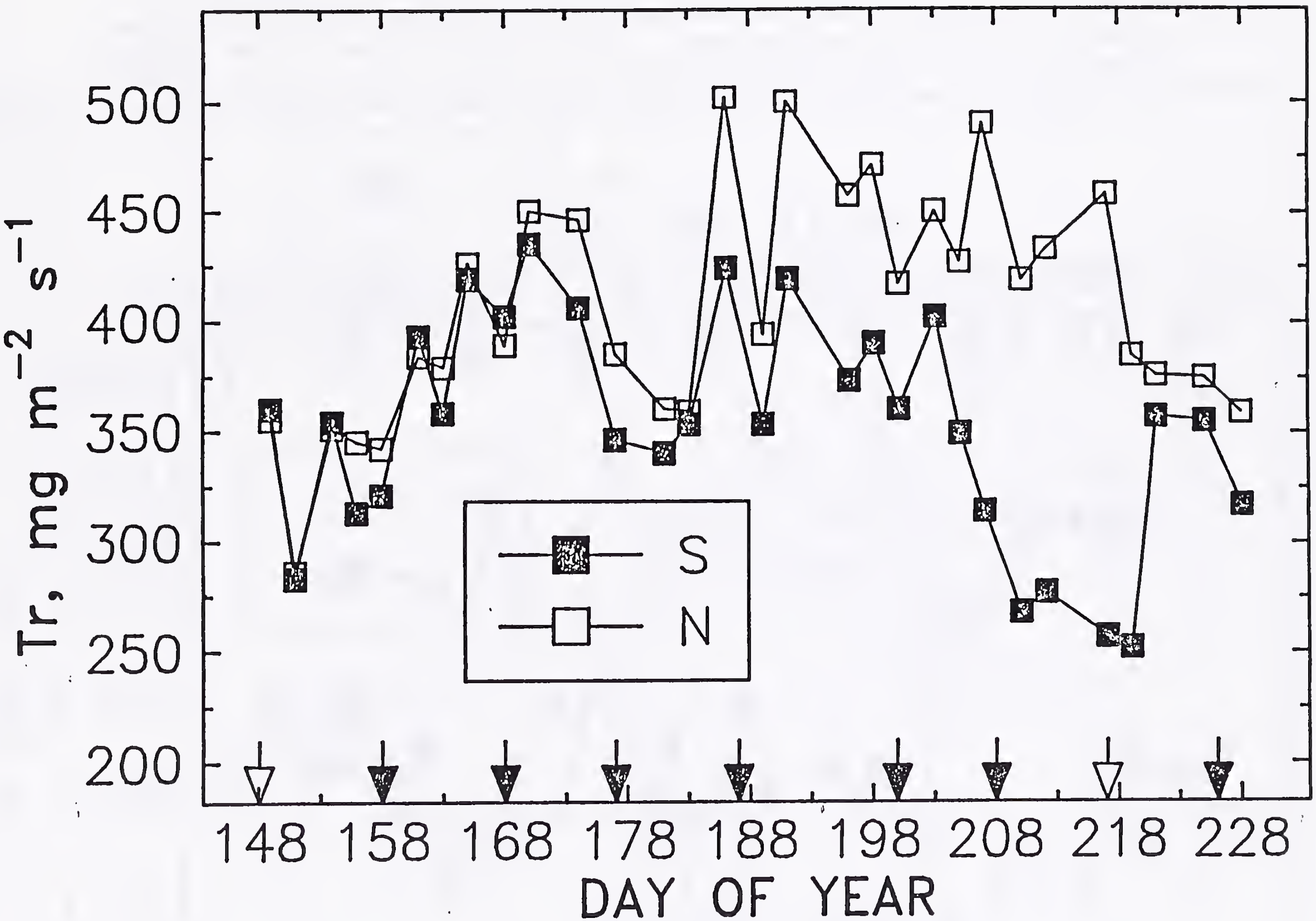

Figure 2. Transpiration (Tr) of stressed (S) and nonstressed (N) guayule between DOY 149 (29 May 1986) and DOY 228 (16 August 1986). SE of difference between any two points is 24.9 mg m^{-2} s^{-1}. Solid and open arrows on the abscissa refer to days when the nonstressed or both the nonstressed and stressed treatments were irrigated, respectively.

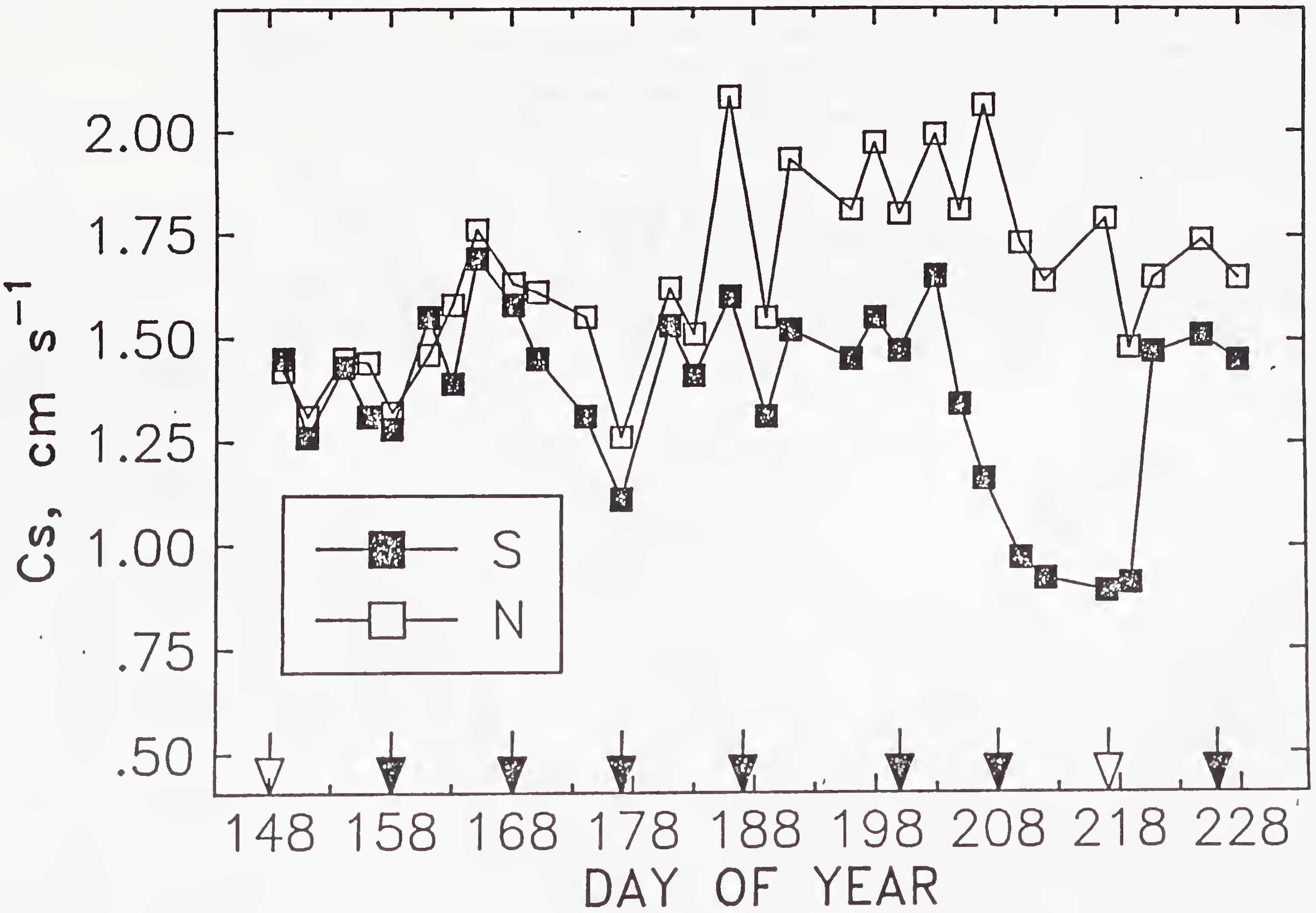

Figure 3. Stomatal conductance to water vapor (Cs) of stressed (S) and nonstressed (N) guayule between DOY 149 (29 May 1986) and DOY 228 (16 August 1986). SE of difference between any two points is 0.12 cm s^{-1}. Solid and open arrows on the abscissa refer to days when the nonstressed or both the nonstressed and stressed treatments were irrigated, respectively.

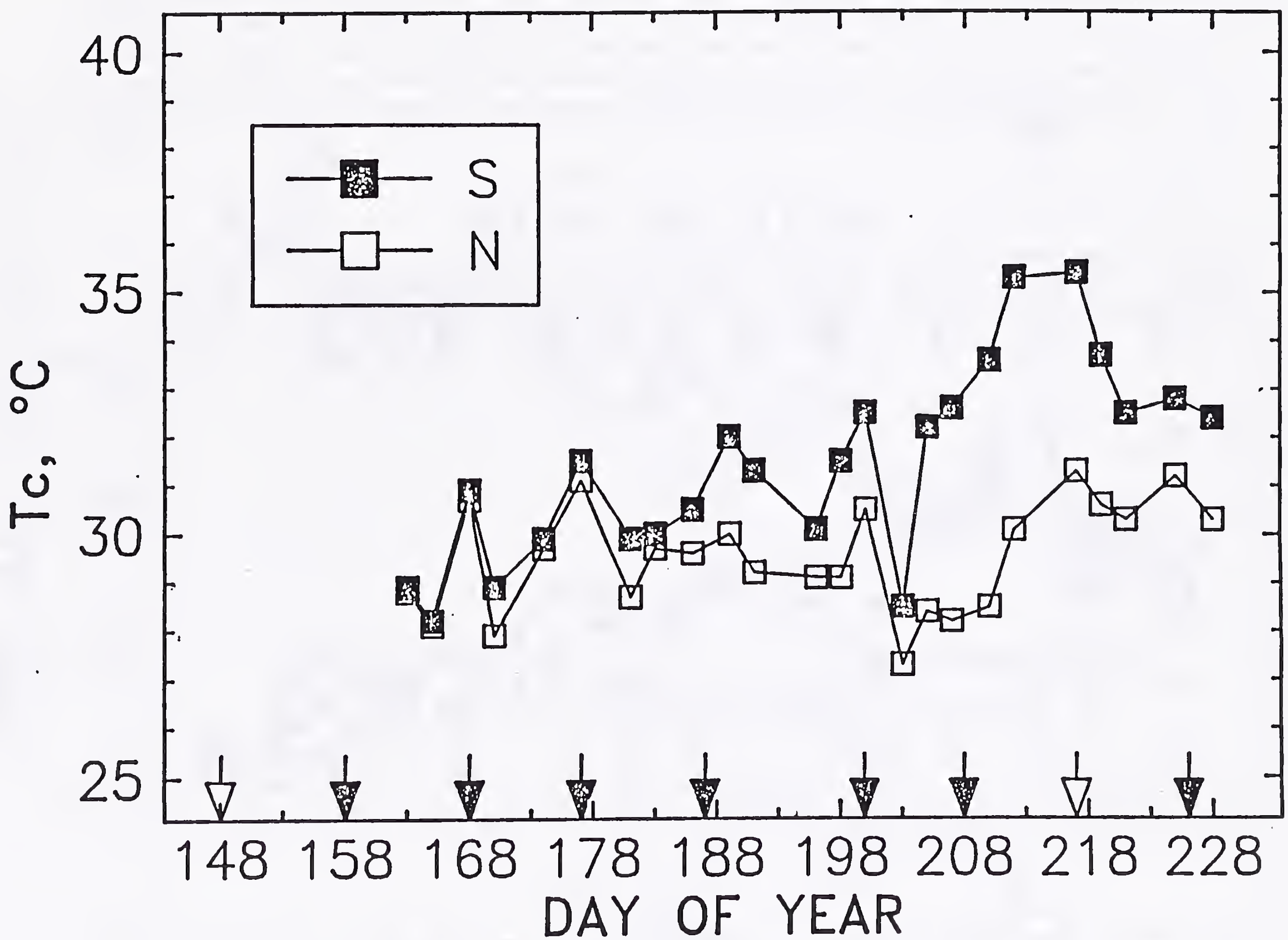

Figure 4. Canopy temperature (Tc) of stressed (S) and nonstressed (N) guayule between DOY 149 (29 May 1986) and DOY 228 (16 August 1986). SE of difference between any two points is 0.43° C. Solid and open arrows on the abscissa refer to days when the nonstressed or both the nonstressed and stressed treatments were irrigated, respectively.

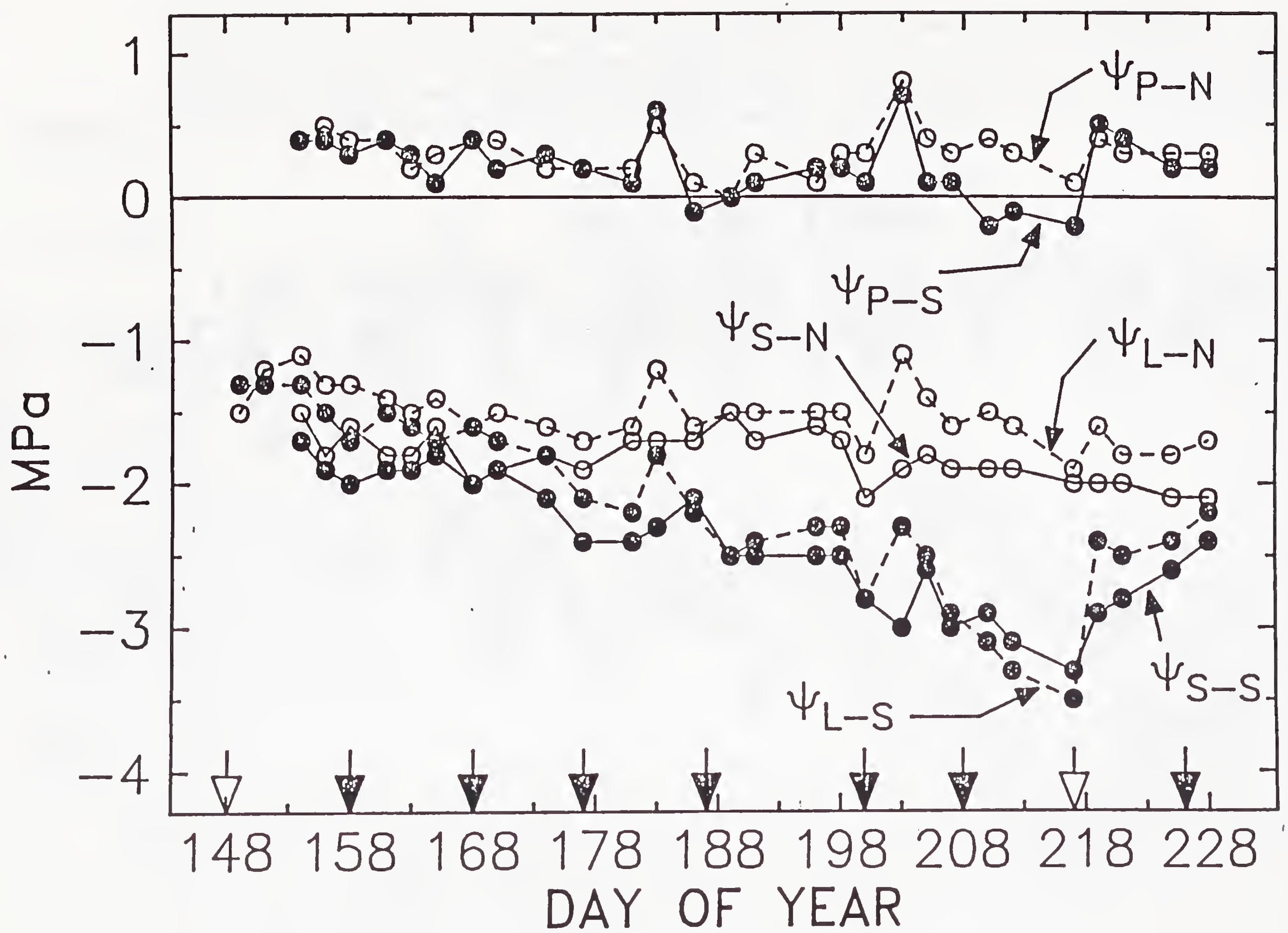

Figure 5. Water potential (Ψ_L), osmotic potential (Ψ_S), and pressure potential (Ψ_P) of stressed (S) and nonstressed (N) guayule between DOY 149 (29 May 1986) and DOY 228 (16 August 1986). SE of difference between any two points of Ψ_L, Ψ_S, or Ψ_P are 0.18, 0.19, and 0.11 MPa, respectively. Solid and open arrows on the abscissa refer to days when the nonstressed or both the nonstressed and stressed treatments were irrigated, respectively.

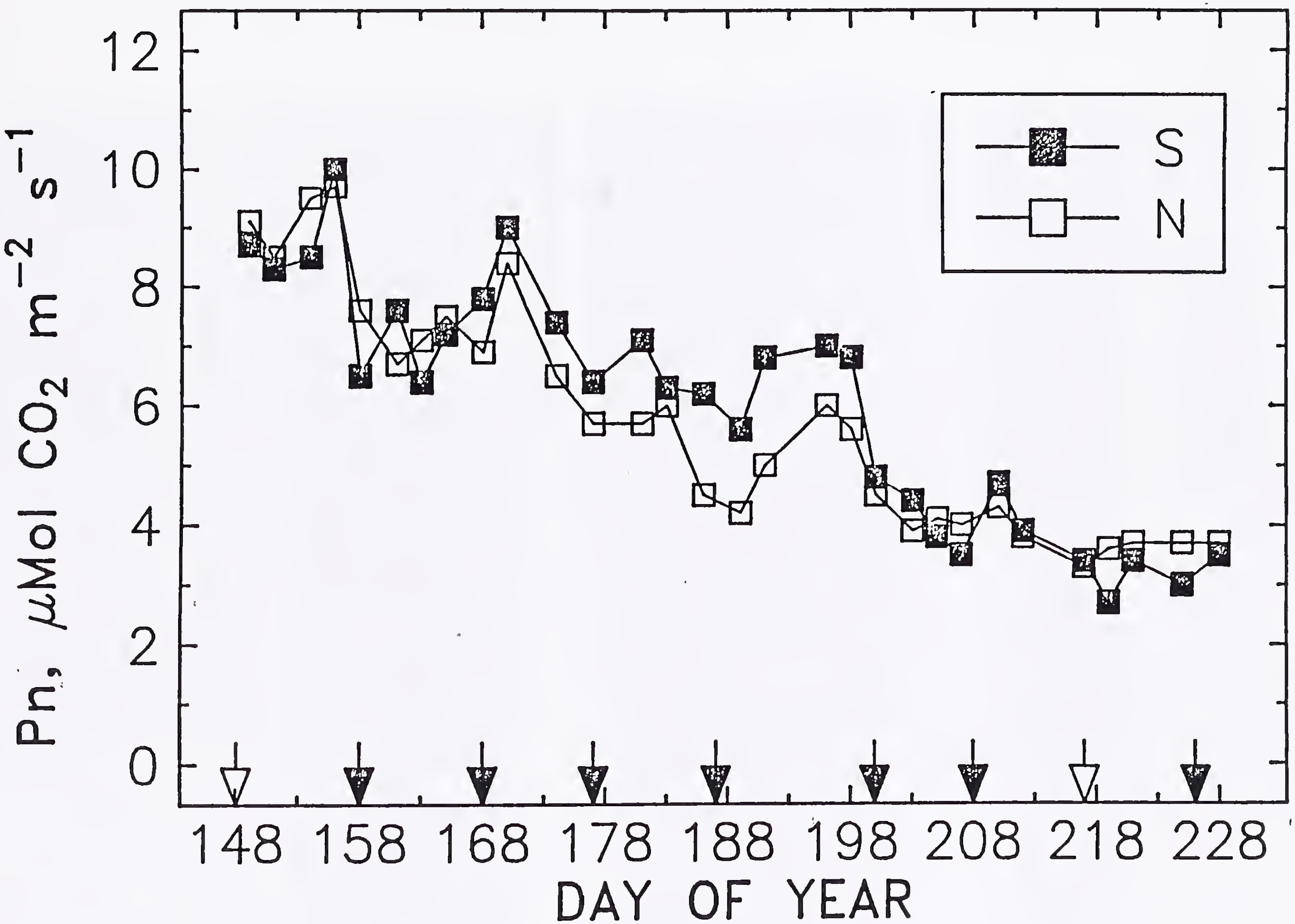

Figure 6. Net photosynthesis (Pn) of stressed (S) and nonstressed (N) guayule between DOY 149 (29 May 1986) and DOY 228 (16 August 1986). SE of difference between any two points is 1.06 μMol m^{-2} s^{-1}. Solid and open arrows on the abscissa refer to days when the nonstressed or both the nonstressed and stressed treatments were irrigated, respectively.

TITLE: EFFECT OF CO_2 TREATMENT ON SOIL PROPERTIES

STRATEGIC PLAN: 1.3.01.1.b 50% CRIS WORK UNIT: 5422-20760-006
1.1.03.1.d 50%

PART I. OPEN-TOP CHAMBER

INTRODUCTION

Our previous studies have shown that the open-top chamber structure affected the CO_2 distribution in the soil profile within the chamber. This experiment was continued in 1986 to find how far this effect extended outside from the chamber. Also, soil air sampling to a deeper depth than previously was made.

PROCEDURE

Soil gas samples were taken with stainless steel microtubing as described in previous annual reports. Sample depths were at 0.05, 0.10, 0.20, 0.40, 0.60, 0.80, and 1.0 M. The needles were placed in the open-top chamber and also outside the chamber spaced at 0.2, 0.6, and 1.2 M from the chamber walls. The ambient air open top chamber were used for the measurements. Chamber blowers were started 26 April 1986 and terminated on 10 October 1986. During this period, weekly soil air samples were taken and analyzed for CO_2 concentration with the infrared gas analyzer. Differential pressure measurements were made at various locations within the chamber. The pressure measurements were made at the soil surface and 10 cm below.

RESULTS AND DISCUSSION

The 1985 soil carbon dioxide data analyzed in terms of the behavior of CO_2 concentration with time for a specific depth are given in Figure 1. The largest difference in CO_2 concentration was present at the 0.6 M depth. The explanation for the CO_2 concentrations becoming similar inside and outside the chamber after the blower was turned off has become clearer. In this situation, the natural decrease in CO_2 production with the lowering of biological activity in the fall played a more important role than the diffusion of CO_2 from the higher to lower partial pressures.

A similar experiment was run in 1986 as in 1985, but included additional sampling depths at 0.8 and 1.0 M. Also, additional sites were located at distances of 0.2, 0.6 and 1.2 M from the chamber wall compared to only one at 2.5 M (designated as the open-field site) for the 1985 experiment. The profile distribution of CO_2 for the "dry" and "wet" treatments as a function of time is presented in Figure 2. Chamber blowers were started on 26 April and turned off on 10 October 1986. Differences in CO_2 distribution were exhibited in the wet and dry soil treatments, with the concentration values inside the chamber lower than the ones outside, and with the lowest concentrations occurring closest

to the chamber walls. For the dry treatment in particular, soil CO_2 concentrations at the deeper depths of 1 M was almost that observed at the 0.05 M depth.

Time sequences of CO_2 concentration for the dry treatment are illustrated in Figure 3 for the 0.05 to 0.4 M and 0.6 to 1.0 M, respectively. Again as in the 1985 results, CO_2 concentration differences inside and outside the chambers were larger at the deeper depths in the soil compared to the shallower depths.

Differential pressure measurements were made inside and outside the chamber while the blower was on and off to determine whether a pressure factor was involved in the CO_2 concentration differences observed in the soil profile for the two different locations. Pressure samplings were taken at the soil surface and 0.1 M below. Pressure distributions differences were greatest close to the air manifold outlet (shown as large circles) and highest closest to the chamber wall (Figure 4). Negative pressure differentials were also present and occurred midway between the air distribution manifolds. While the pressure differences appear low, continuous imposition of such a condition could be responsible for the flushing of soil gases. This explanation is a very crude qualitative picture of what is happening in the chamber and more detailed measurements and application of diffusion and mass flow movement of gases is necessary.

The open-top chamber system does affect the soil air relative to CO_2, and presumably, the effects are similar for the "ambient CO_2" or check and the "enriched CO_2" chambers so that it would be acceptable to compare these two type of treatments in terms of the CO_2 levels only.

PART II. CARBONATED WATER IN TRICKLE IRRIGATION

INTRODUCTION

The application of carbon dioxide enriched irrigation water for improving crop yield was explored earlier by Bucks and Nakayama (1980). The use of this technique in conjunction with the open-top chamber method for carbon dioxide exposure of plants is being further investigated with the cotton plant. This part of the overall study was initiated to determine the effect of CO_2-saturated irrigation water applied with trickle irrigation system on the pH and CO_2 status of the soil. The plant growth and yield parts are being explored by another group.

PROCEDURE

The CO_2-saturated water was produced with a commercial-type carbonator. This water was applied with the in-line, long-path emitter. The trickle line was laid on the soil surface and along the plant row. Emitter spacing was 30 cm. Irrigation was made during the daylight hours, usually between 8:30 a.m. and 2:00 p.m. pH measurements were made near the dripper during the irrigation period. Also, gas samples were taken at various depths in the soil along the trickle line at various times.

The manner in which carbonated water affects soil pH was determined by measuring soil pH at various times following trickle irrigation with the carbonated water. A temperature compensated glass electrode was inserted into the soil paste where the water dripped onto the soil. Soil CO_2 composition was determined at various depths in the soil profile using the gas sampling technique with specially prepared hypodermic needles, as described in Part I.

RESULTS AND DISCUSSIONS

The pH of the irrigation water was lowered from 7.5 to 5.1 by the CO_2 gas saturation treatment (Table 1). This carbonated water, when applied to the field, lowered the soil pH by approximately 1.5 units. For this example, Table 1, carbonated water was run from 0830 to 1300. When irrigation was stopped, the soil pH gradually increased and reverted back close to the check soil pH overnight.

The CO_2 concentration in the soil profile was also affected by the carbonated water treatment as illustrated in a comparison of Figure 5 of the check and Figure 6 of the treated plot. A rapid increase in CO_2 in the order of 5 to 6 fold was present soon after the irrigation treatment was started at the 0.05 and 0.1 meter depths. While a similar dramatic increase was not observed at the 0.2, 0.4, and 0.6 meter depths in the carbonated water treatment, the CO_2 concentration was higher in the treated than untreated at the respective depths, indicating that the carbonated water and/or CO_2 gas could move downwards into the deeper depths, and that the plants are using a different soil gas soil-pH environment in the treated compared to the untreated plot. Similar types of behavior was observed with soil pH and soil CO_2 concentration using subsurface trickle irrigation system (Nakayama and Bucks, 1980).

SUMMARY

The soil CO_2 regime can be greatly affected by the open-top enrichment chamber. Over a five-month operational period when cotton plants were exposed to CO_2-enriched air, the soil CO_2 concentration in the soil profile within the chamber was drastically changed. The CO_2 concentration at 1 M depth, which is normally about 60 times that of the shallower depths, became almost equal to that at the 10-cm depth.

Where CO_2-saturated irrigation water is used for CO_2 enrichment, the acidity of the water was increased. The soil pH of the calcareous soil was lowered by approximately 1.5 pH unit with the CO_2-water treatment. The soil CO_2 concentration at the deeper depths were also increased and this may help improve the availability of minor nutrients to the plant roots.

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PERSONNEL

F.S. Nakayama and B.A. Kimball

TABLE 1. Effect of Carbonated Irrigation Water on Soil pH.

	Irrigation Water		Soil	
Time	Check	CO_2-treated	Check	CO_2-treated
0830	7.47	5.05	8.03	5.80
0940	7.63	5.16	7.50	5.83
1130	7.49	5.11	7.40	6.17
1300	7.52	5.13	7.55	5.98

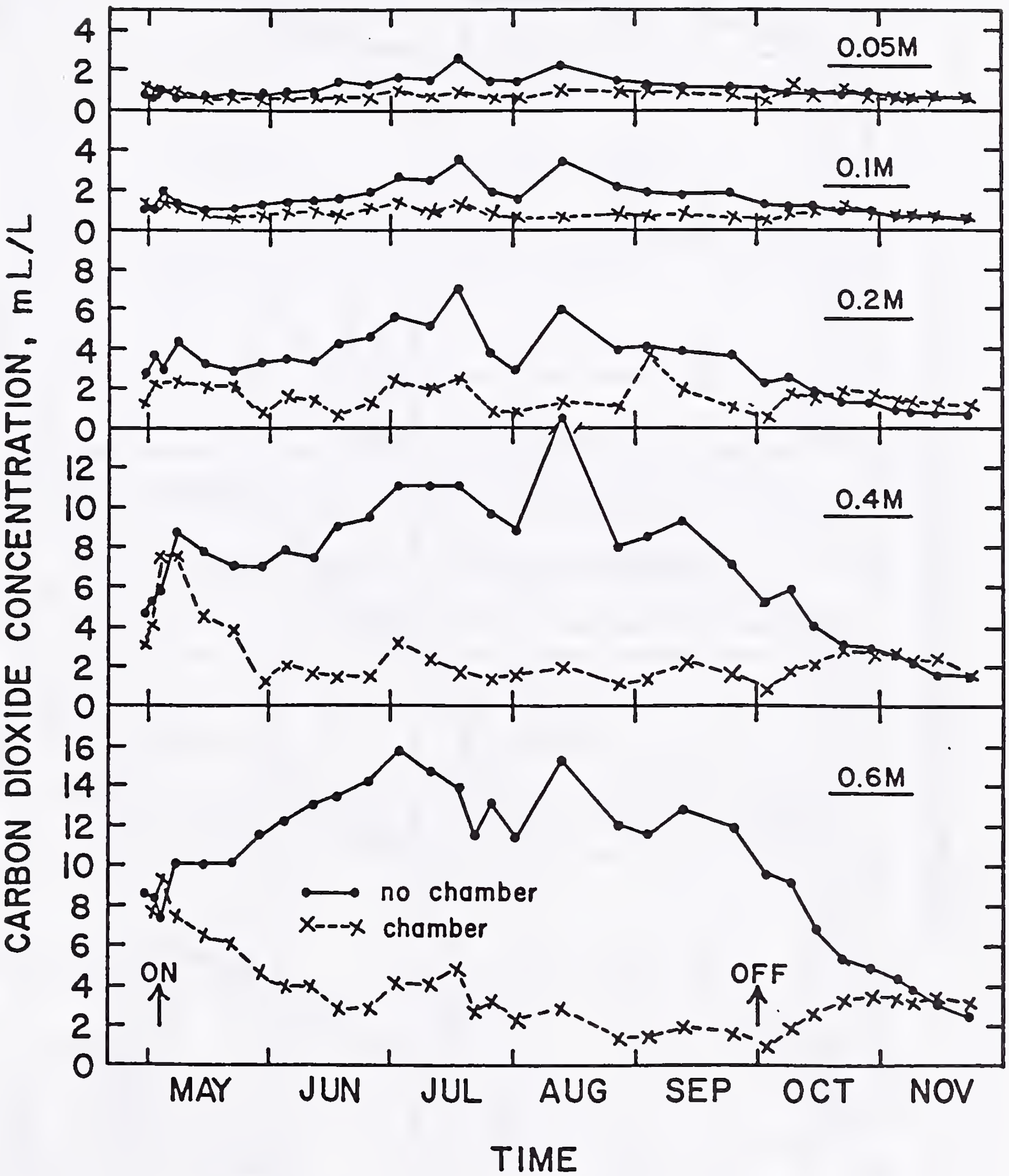

Fig. 1. Soil carbon dioxide concentration in the soil profile at various times inside and outside the open-top chambers. (Blower started 02 May and stoppped 02 October 1985.)

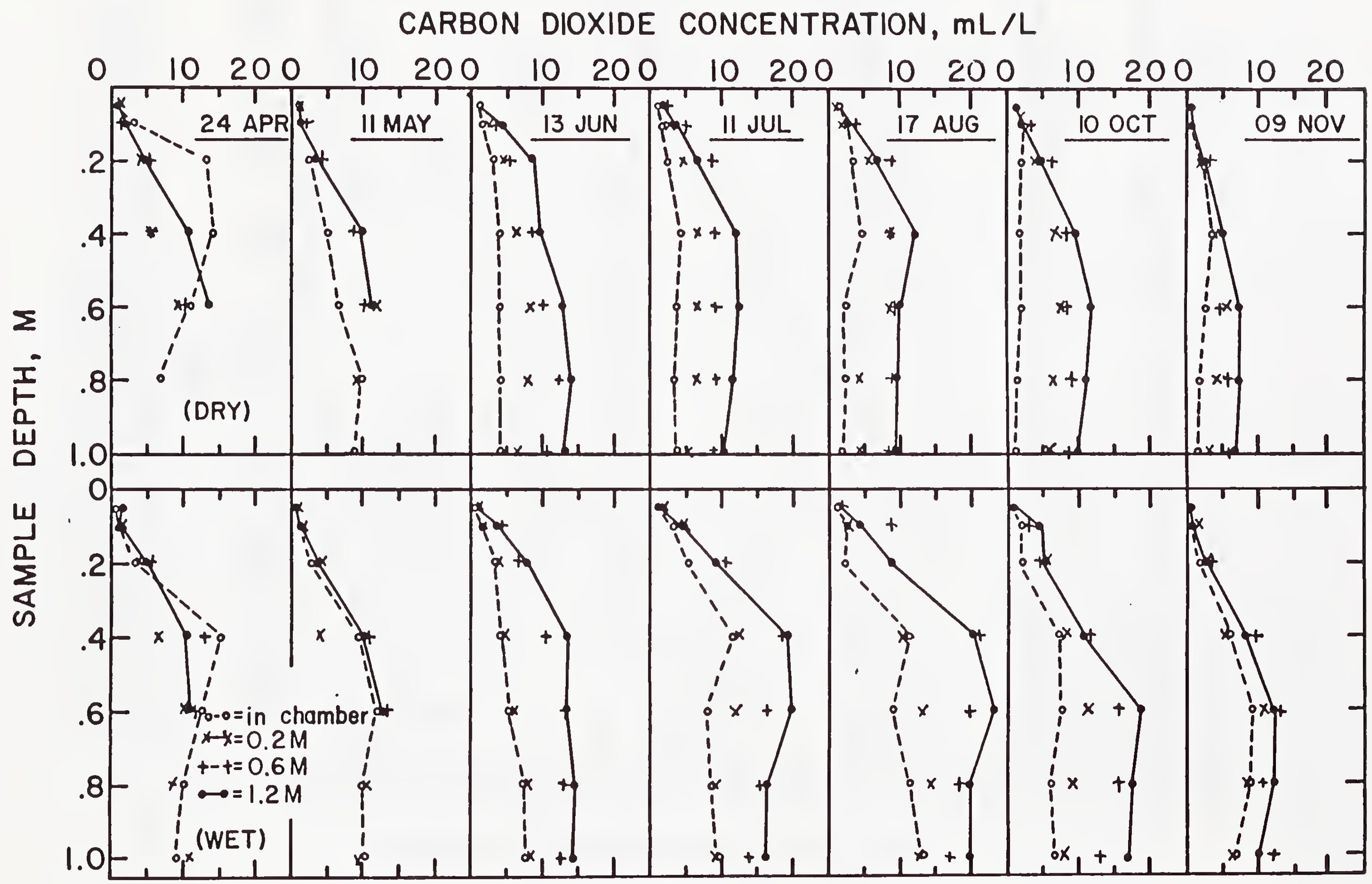

Fig. 2. Soil carbon dioxide concentration profiles at the various depths X distance from chamber combination during and after the cotton planting. (Blower started 26 April and stopped 10 October 1986.)

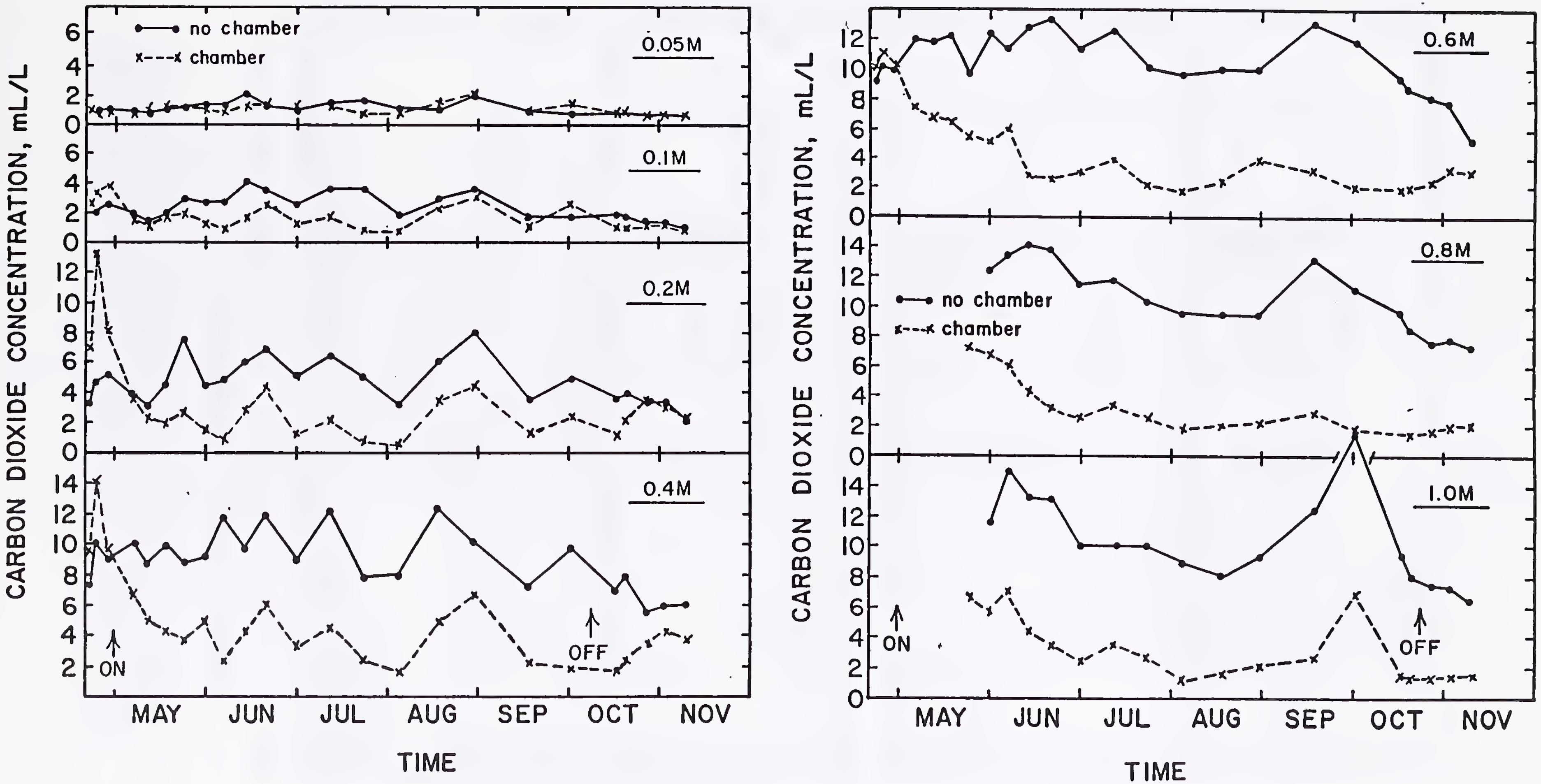

Fig. 3. Soil carbon dioxide concentration at depths of 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 M inside and outside the open-top chamber.

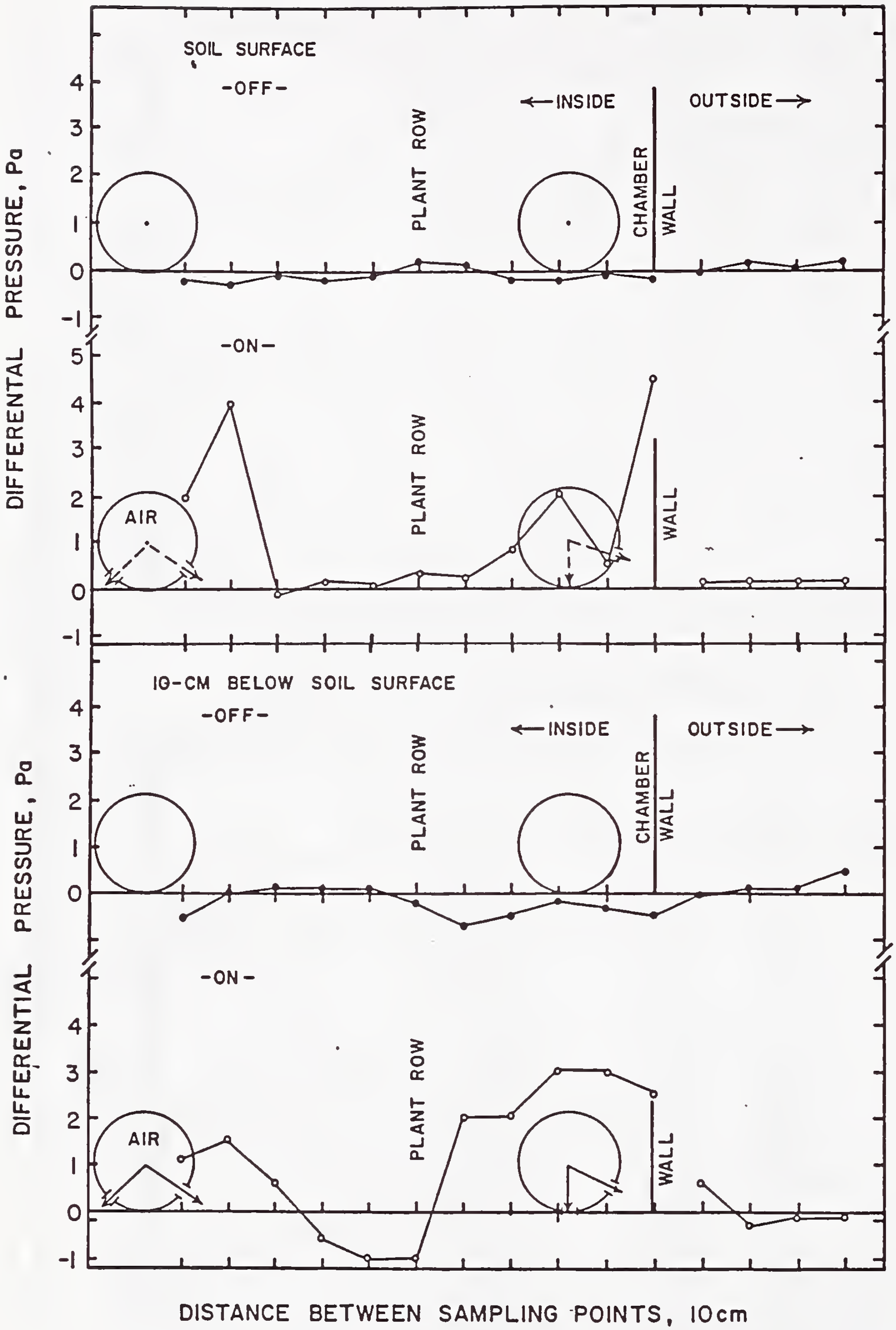

Fig. 4. Differential pressures at and 0.1 M below the soil surface located the soil surface inside and outside the open-top chamber with the blower "off" and "on".

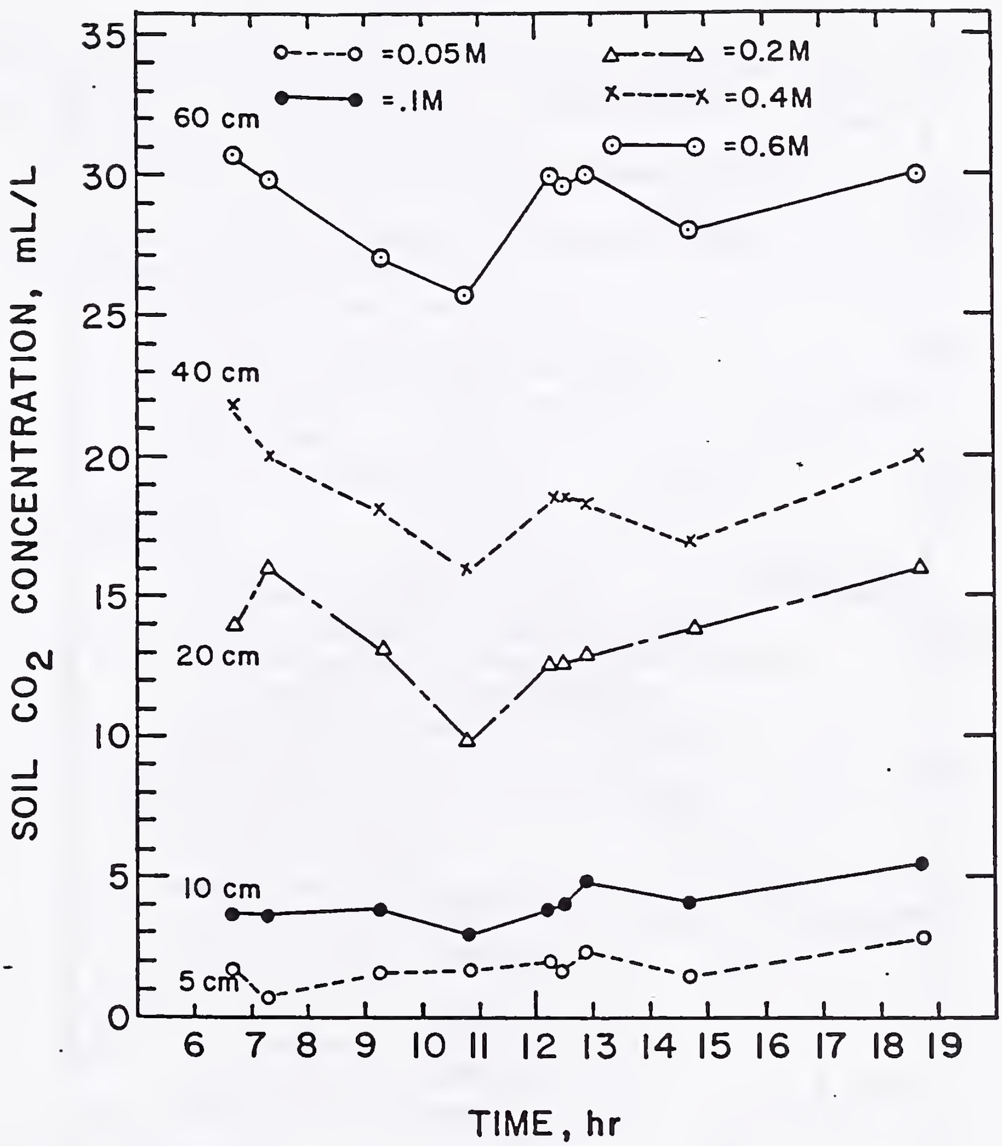

Fig. 5. Soil carbon dioxide concentration at various depths for the check plots under trickle irrigation.

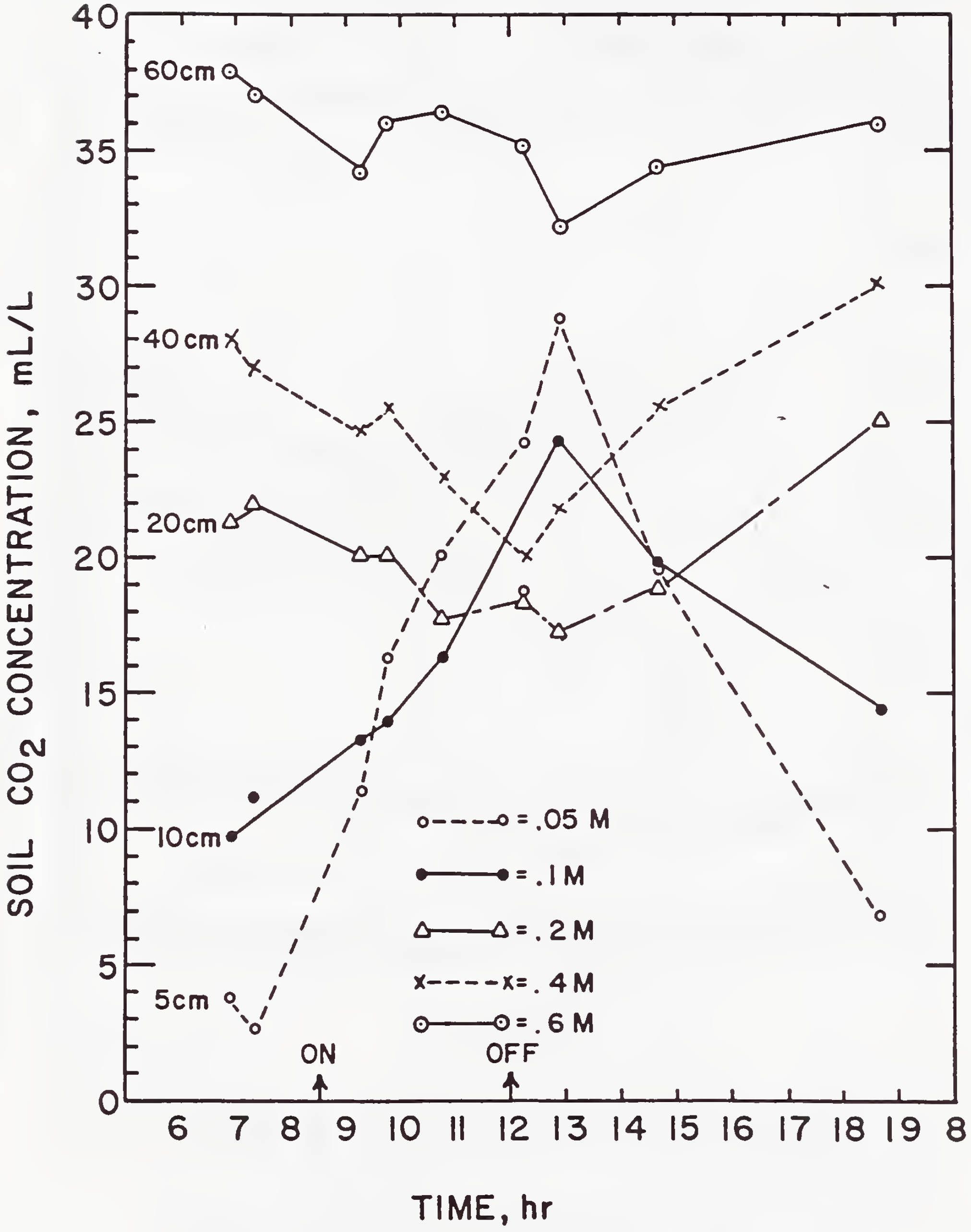

Fig. 6. Soil carbon dioxide concentration at various depths for plots with CO_2-saturated trickle irrigation.

TITLE: EFFECTS OF INCREASING ATMOSPHERIC CO_2 ON YIELD AND WATER USE OF CROPS

SPC: 1.3.01.1.b CRIS WORK UNIT: 5422-20760-006

OUTLINE

INTRODUCTION

1985 OPEN-TOP CHAMBER EXPERIMENT - FURTHER RESULTS
- A. Analysis of Carbon Isotopes
- B. Modulus of Elasticity and Non-osmotic Volume

1986 OPEN-TOP CHAMBER CO_2/WATER/NITROGEN EXPERIMENT
- A. Materials and Methods
  1. Culture of experimental crop
  2. Irrigation and water use
  3. Nitrogen applications and uptake
  4. Carbon dioxide concentrations
  5. Statistics
  6. Modeling of plant growth

- B. Results
  1. Leaf area, flower production, boll retention, biomass, and yield
  2. Elemental analysis of leaf tissue
  3. Photosynthesis and stomatal conductances at chamber CO_2 concentrations
  4. Photosynthetic responses to changes in CO_2 concentration
  5. Stomatal responses to injected ABA
  6. Leaf starch content
  7. Stomatal densities
  8. Leaf temperatures
  9. Leaf water potential, relative leaf water content, and dry matter content
  10. Pan evaporation
  11. Development of pink bollworms
  12. Soil atmosphere CO_2 concentrations and pressure gradients
  13. Aerodynamic resistance

FIZZ/FACE EXPERIMENT
- A. Materials and Methods
  1. Overall design, plot plan, and culture of experimental crop
  2. FIZZ/irrigation system design and CO_2/water use
  3. FACE system design and CO_2 use
  4. Soil pH and CO_2 concentrations
  5. Atmospheric CO_2 concentrations

B. Results
1. Leaf area, flower production, boll retention, biomass, and yield
2. Elemental analysis of leaf tissue
3. Photosynthesis and stomatal conductance
4. Leaf starch content
5. Leaf water potential, relative leaf water content, and dry matter content

CO_2-TEMPERATURE INTERACTION EXPERIMENT
A. Prior Work
B. New Experiments
C. Old Experiments
D. Results and Discussion

SUMMARY AND CONCLUSIONS

REFERENCES

PERSONNEL

INTRODUCTION

To determine the effects of the increasing atmospheric CO_2 concentration on the growth and water use of crops, the U. S. Water Conservation Laboratory and the Western Cotton Research Laboratory cooperatively conducted three experiments during 1986. In the largest experiment, the effects of the three-way interaction between increased CO_2 concentration, water-stress, and low fertility on the growth of cotton were investigated. Secondary objectives were to determine the effects similarly on the physiological determinants of crop yield, on water stress and stomatal behavior, and on biochemical reactions that limit photosynthesis. Open-top chambers were used to confine the CO_2 around the field-grown cotton.

In many prior experiments reviewed by Kimball (1983) conducted under mostly ideal conditions in greenhouses and growth chambers, and also in field experiments conducted by us (Kimball _et al_. 1983, 1984, 1985) under well-watered and fertilized conditions, most crops and cotton in particular have produced large increases in yield with a doubling of CO_2 concentration. However, much of the world's agriculture and the unmanaged biosphere suffer often from insufficient water and nutrients. Consequently, a multivariate experiment was needed to determine how productivity will be affected under conditions of water and nutrient stress in the future high CO_2 world.

In the second experiment, the effects of CO_2 on cotton growing in an open field were observed. The CO_2 was applied using two methods - (1)

irrigating with carbonated water (fizz water) and (2) releasing gaseous CO_2 at the soil surface, a free-air CO_2 enrichment (FACE) experiment. Prior greenhouse experiments have shown large increases in cotton yield when irrigated with fizz water. A field experiment was needed to determine whether such treatment would be a practical means to improve farm cotton yields. Similarly, a season-long FACE experiment had never been conducted on cotton. Because our prior open-top chamber experiments have shown that cotton yield can be increased about 80% with a doubling of CO_2, a free-air release experiment was needed to see whether this treatment has any possibility for farm application. More importantly however, the FACE experiment produces a CO_2 enriched atmosphere with none of the environmental changes produced by a chamber, so this experiment was also needed to determine whether a soil surface release of CO_2 would be an appropriate means to conduct future experiments intended to study the effects of the increasing atmospheric CO_2 concentration on vegetation.

The interaction between CO_2 enrichment and temperature was investigated in the third experiment. Successive plantings of crops with short life cycles were grown continually throughout a year, and the CO_2 stimulation of growth was observed as temperature followed its normal seasonal change. As will be discussed in detail, the effects of CO_2 were found to be highly temperature dependent.

1985 OPEN-TOP CHAMBER EXPERIMENT - FURTHER RESULTS

A. Carbon Isotope Analyses

The $^{14}C/^{12}C$ and $^{13}C/^{12}C$ ratios from cotton lint harvested from the 1985 open-topped CO_2-enrichment study are shown in Table 1. These data were collected in an attempt to document the CO_2 content of the atmosphere in which the plants were grown using the technique of Enoch _et al._, (1984). Because the CO_2 used for enrichment is derived from fossil sources and has a different ^{14}C and ^{13}C content from modern atmospheric CO_2, it is possible to determine the CO_2 content the plant "perceived" as it fixed CO_2 by the photosynthetic process. The ^{14}C and ^{13}C ratios were determined by the Laboratory of Isotope Geochemistry at the University of Arizona, Tucson.

The "perceived" CO_2 contents of the enriched chamber from the two isotopes are not in agreement with each other. The higher content calculated by the ^{13}C data are typical of the calculation made by Enoch _et al._ in their CO_2-enrichment studies. The plant discrimination against ^{13}C and ^{14}C are sufficiently different so the same indices cannot be used in both formulas. However, there is not yet enough data to derive accurate transformation indices for the processes. Thus, the calculation remains imprecise.

In general, it appears that the 650-D treatment "perceived" a lower CO_2 content than the 650-W treatment. This may be due to the lower LAI of

this treatment which could result in greater penetration of gusts of ambient air from the open-top of the chamber into the crop canopy, although the sampling point for the CO_2 control system was 10 cm above the canopy in both treatments.

B. Modulus of Elasticity and Non-osmotic Volume

Theory

Additional analyses of the "pressure-volume" curves obtained in 1985 were conducted. Figure 19 of Kimball et al. (1985) shows a plot of reciprocal leaf water potential against relative leaf water content. The upper curved portion is where turgor potential is greater than zero, and slope of the curve is related to the elasticity of the cell walls (Sinclair and Venables, 1983). The definition of the modulus of elasticity , ε, is:

$$\varepsilon = V(dt/dV) = V(dP-d\pi)/dV \quad (1)$$

where t is the turgor potential, V is the volume of leaf cell water, P is the total potential and π is the osmotic potential. For small changes in cell water volume where V can be considered a constant, dV is proportional to the change in relative leaf water content, dR (Jones and Turner, 1978). Thus, restricting the analysis to the region near the zero turgor point,

$$\varepsilon \approx (dP-d\pi)/dR \quad (2)$$

The modulus of elasticity was determined from the-pressure-volume curves by fitting a quadratic to the curved portion and a straight line to the linear portion. For the linear portion we can write:

$$(1/\pi) = a + bR \quad (3)$$

where a and b are the intercept and slope, respectively of the line. Differentiating and rearranging

$$d\pi/dR = -\pi^2 b \quad (4)$$

Similarly for the the curved portion,

$$(1/P) = a' + b'R + c'R^2 \quad (5)$$

Differentiating and rearranging

$$dP/dR = -P^2(b' + 2c'R) \quad (6)$$

At the zero turgor point where the straight line meets the curve, $\pi = P$, so substituting 4 and 6 into 2 yields

$$\varepsilon \cong -P^2(b' + 2c'R - b) \tag{7}$$

The "non-osmotic volume" is the volume of water that does not osmotically participate in cell activities, and theoretically it should be that amount of water where $(1/\pi) = 0$ in Figure 19 of Kimball et al. 1985, i.e., it is the amount of water where the straight line crosses the relative leaf water content axis. Using 3, the non-osmotic water content, R', where $(1/\pi) = 0$ is:

$$R' = -a/b \tag{8}$$

Using the pressure-volume curves drawn by eye to the eight (usually) data points, four new points were digitized. The first was on the straight line, the second at the zero turgor point intersection of the line and curve, the third on the curve fairly close to the second, and the fourth further up the curve. From the first two points, a and b were calculated, and then from the last three points, a', b', and c' were also calculated. These coefficients were substituted into Equations 7 and 8 to determine the modulus of elasticity and the non-osmotic volume for each of the p-v curves.

The predawn and afternoon mean moduli of elasticity are presented in Tables 2 and 3, respectively. The overall mean for the predawn and afternoon samples were 5.32 and 5.63 MPa. However, the inherent variabilty in the data of the p-v curves was somewhat large, and the variability of the slopes of the curves was even larger, so consequently, it was difficult to detect any treatment differences. In the predawn data there appears to be an interaction between irrigation and CO_2 with the elasticity decreasing with increasing CO_2 under well-watered (wet) conditions, but little effect under water-stress (dry) conditions. This suggests that the CO_2 might have made the cell walls more flexible in that there would be a smaller pressure change per volume of cell water change. The interaction was statistically significant (0.05 level) only when biweeks were considered as a main plot effect, however. (See the statistics section of the 1986 methods section for more details about biweek repeated sampling.) Next, considering the afternoon data (Table 3), no interactions or main treatment effects were significant no matter how biweeks were handled. Thus, these data do not indicate a consistent effect of CO_2 or irrigation on cell elasticity, but any such differences would have had to have been fairly large to be detected.

The predawn and afternoon mean non-osmotic relative leaf water contents are presented in Tables 4 and 5, respectively. The overall means were 21.3 and 17.7%. Like the elasticity data, however, variability was large. In this case the error was primarily due to the long extrapolation of the fitted line (Equation 3) from the region of the data points (70-95% relative leaf water content) down to where it crossed the axis around 20%. No significant treatment differences were detected from the predawn samples. CO_2 appeared to have a significant effect in the

afternoon samples if biweeks are considered to be a main plot treatment. However, the 500 treatment was below the ambient and 650, so it seems unlikely that these CO_2 effects are real. Thus, as with the elasticity data, there do not appear to have been any consistent effects of CO_2 or irrigation on non-osmotic relative leaf water content, but any such differences would have had to have been fairly large to be detected.

1986 OPEN-TOP CHAMBER CO_2-WATER-NITROGEN EXPERIMENT

A. Materials and Methods

1. Culture of experimental crop

The cotton crop was grown on the field just west of the Western Cotton Research Laboratory, Phoenix, Arizona, on the same plots as the 1984 and 1985 experiments (Kimball *et al.*, 1984, 1985). A plot plan is shown in Figure 1. The soil is Avondale clay loam (Fine-loamy, mixed (calcareous), hyperthermic, Anthropic Torrifluvent). Following the 1985 experiment, all equipment was removed from the field, and it was plowed. During early March, 1987, it was furrowed and flood irrigated with approximately 15 cm of water. Using a two row planter, cotton (Deltapine-61) was planted on 31 March 1986. A pre-emergent herbicide, pendimethalin (Prowl[1/]), was applied at a rate of 2 liters/ha.

Following the planting operations, neutron access tubes were installed in each plot. One was installed in the middle row in the exact center of the planned site for the open-top chamber. A companion tube was installed about 500 mm north and 25 mm west of the center tube. As before, the gravel layer underlying the field prevented installation of the tubes deeper than about 800 mm at the north end of the field, but moving southward, they could be installed deeper, down to 1500 mm for the southmost plots.

Open-top chamber installation commenced on 2 April and was completed by about 22 April. The same 3 m by 3 m by 2 m high chamber design was used as in the last experiment (Kimball *et al.*, 1985). The tops of the beds were knocked off with a rake on 8 April, and the cotton was mostly emerged by 10 April. A few gaps were filled by some additional planting on 11 April and some transplants on 22 April. On 1 May the center row in each chamber was thinned to 10 plants per square meter with the removed plants used as the first initial destructive harvest. Border rows were also thinned at that time. The east and west rows inside the

[1/] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the listed product by the U. S. Department of Agriculture.

chambers were similarly thinned (destructively sampled) during the next two weeks. A drip irrigation system was installed on 11 April. Enrichment with CO_2 was started on 25 April.

Insects were a problem again in 1986. Early season thrips were effectively controlled with spray applications of Orthene as listed in Table 6. By far the most serious infestation was due to leaf perforators during the last week of July. Apparently they were resistant to the malathion sprays made earlier (Table 6) while their predators weren't, so their numbers greatly increased and caused much visible damage throughout the field. Fortunately, the damage within the open-top chambers was much less than in the open field as a whole. Finally sprays of Dimilin and Pydrin on 12 and 23 August, respectively, brought them under control in time to save the experiment.

2. Irrigation and Water Use

The drip irrigation system was modified to have emitters (rated at 2 liters/hour at 10 m of head) spaced every 0.25 meters. The closer spacing provided an even distribution of water along the rows and eliminated the need to manually move the lines as was done in 1985. The same formula, Equation 1, was again used to calculate the amount of water to apply to the well-watered (wet) plots:

$$\text{irrigation amount} = \text{pan evaporation} \times (\text{LAI}/3) \qquad (9)$$

where LAI is the leaf area index projected from the previous week's destructive plant harvest. Above a LAI of 3, the irrigation amount was the pan evaporation amount of the previous week. The pan evaporation was the amount of water that evaporated from a Class A pan located beside the field during the previous week. As will be discussed later, the pan evaporation rate in the chambers was 5% more than the open field but that from pans in the open field was 38% less than from a pan beside the field, so the amount of water applied to the well-watered plots should have been a generous amount. The dry or water-stressed plots received 2/3 of the amount of water applied to the wet plots.

Rainfall was measured from gauges beside the field, and the rainfall amounts were subtracted from the calculated irrigation requirements each week. Also, any shortage (or excess) of the actual amount applied from the target application for a particular week was added (or subtracted) from the target application for the next week.

The irrigation system was split into four sections: wet-N^+, wet-N^-, dry-N^+, and dry-N^- plots each being irrigated together. The amounts applied were measured using newly calibrated water meters, two per section. The duplicate meters always agreed to within about 1%. The amounts of irrigation water and rainfall applied to the wet and dry N^+ plots are given in Table 7 and plotted in Figure 2 against day of year, ignoring the initial early irrigations used for germination and stand

establishment. The graph for the N^- plots is essentially identical and therefore has not been included. Also plotted in Figure 2 are the cumulative pan evaporation (x LAI/3) from Equation 1 for the wet plots and 2/3 of the wet amount for the dry plots. It is obvious that we were able to closely track the adjusted pan evaporation curves most of the season. The deviations near day 235 were caused by a clogged filter which reduced the flow rate, followed by an over-compensating irrigation which was immediately followed by rain.

The recommended water application curve from Erie et al., (1981) for well-watered cotton is also shown in Figure 2 for the wet plots and 2/3 of the wet curve for the dry plots. The total amount of water applied over the whole season (1349 mm for the wet plots, Table 7) exceeded the Erie et al., amount (1050 mm) by 28%, indicating we were applying a generous amount of water to the wet plots (or conversely that the Erie et al. curve may be somewhat low). Indeed the amount of water we applied to the dry plots (903 mm) was almost the Erie et al., amount, yet the dry treatment cotton plants clearly were stressed and grew and yielded less than the well-watered plants.

The total water use for each of the plots is presented in Table 8. The change in soil water storage between 10 April and 30 September was calculated from neutron soil moisture measurements made on those dates. The wet plots gained an average 8 mm of water during the season, whereas the dry plots were an average 75 mm drier at the end of the season. There was a tendency for the plants in the 650 CO_2 plots to use slightly more water than those in the ambient plots, but the difference was not statistically significant. Compared to the amounts of water applied by irrigation and rainfall, the soil storage changes were very small (0.6% for the wet plots and -8.3% for the dry plots). Therefore, the total water use was very close to the total amount of water applied.

3. Nitrogen Applications and Uptake

Six soil samples were taken before planting from the plowed layer of the field at random locations. The mean NO_3^--N content of these samples was 22.7 mg/g with a standard deviation of 5.5. At the end of the season, 2 soil samples were taken from each plot and again analyzed for NO_3^--N. Averaging over reps, subsamples, and the other treatments, the mean NO_3^--N contents for the wet and dry plots were 5.1 and 5.0 mg/g, respectively. Similarly, the means for the ambient and 650 $\mu\ell\ \ell^{-1}$ CO_2 treatments were 5.6 and 4.6 mg/g, respectively. One would expect the largest difference to be between the none-added (N^-) and the added (N^+) fertilizer nitrogen treatments, but the N^- and N^+ means were 4.6 and 5.6 mg/g, respectively. None of these mean differences were significantly different, but the tendency was for the high CO_2 plants to have extracted more NO_3^- and for the N^- plots to have slightly less NO_3^- at the end of the season.

Total soil N was not analyzed, so the total change in soil N can not be computed. However, using a mean change of soil NO_3^--N content of 22.7 -

5.1 = 17.6 mg/g, assuming a bulk density of 1400 kg/m^3 and a soil depth of 0.15 m, the change in soil NO_3^--N content on a hectare basis was about 37 kg/ha.

The NO_3^--N content of the irrigation water was was analyzed by a commercial laboratory on a sample taken on 26 August 1986 and found to be 2mg/liter. Multiplying by the amount of applied irrigation water, the wet and dry plots received 6 and 4 kg/ha, respectively, of N from the irrigation water itself, or about 5 kg/ha on the average.

Starting on 13 May, urea was injected into the irrigation water applied to the N^+ plots. About 0.6 kg of urea was dissolved into about 15 liters of water to make a stock solution, which was injected into the irrigation pipe using a commercial water-pressure-driven suction device. The actual injection took about half an hour near the middle of each irrigation with unfertilized water passing through the system before and after each injection. The total amount of urea-N applied was 96 kg/ha. Due to a communication error, this amount of N applied was half that planned. The N applications are summarized in Table 9.

The NO_3^--N content of the leaf petioles was determined from leaves sampled on 15 days during the season, and these results are presented in Figures 3 and 4. Each data point is a composite of 4 petioles from the leaves used for water potential analysis. In spite of the subsampling, there was obviously a large amount of scatter in the data, and the differences between the N^- and N^+ treatments were not significant. Moreover, there was no visual difference in greenness or yellowness between the N^- and N^+ plots that we could perceive, and we feared that we did not truly have a nitrogen-stress treatment. (And indeed, not as much N had been applied to the N^+ plots as we thought.) It wasn't until we examined the yield differences at the end of the season, as will be discussed later, that any effect of nitrogen deficiency was detected.

4. Carbon Dioxide Concentrations

CO_2 concentrations were continually monitored, as described previously (Kimball et al. 1983, 1984). The only significant change was a switch to Dayton Speedaire oil-less diaphragm sampling pumps rated at 24 liter/min at 70 kPa. These pumps have metal bodies and more rugged construction than those used previously. They have been very reliable -- not one failed during the 1986 season.

The diurnal patterns of mean CO_2 concentrations for the 1986 experiment are presented in Figures 5-8. Like the previous years, it is again apparent that ambient concentrations underwent a diurnal variation from about 350 $\mu\ell\ \ell^{-1}$ in daytime to 400 $\mu\ell\ \ell^{-1}$ at night. The enriched plots also had some diurnal variation but less pronounced because of the controlled set point at 650 $\mu\ell\ \ell^{-1}$. After sunrise each day, the concentrations decreased below set point for an hour or two until the system responded to the higher level of atmospheric turbulence. After

sunset, concentrations rose above set point until they similarly responded to calmer night conditions.

The overall CO_2 concentration means and the standard deviations of the individual observations are tabulated in Table 10. In 1986, they averaged 356 ± 39 and 643 ± 72 $\mu\ell\ \ell^{-1}$ during daytime, 389 ± 50 and 657 ± 64 during nighttime, or 371 ± 48 and 649 ± 69 $\mu\ell\ \ell^{-1}$ averaged over a whole (24 hr) day for the ambient and "650" treatments, respectively.

5. Statistics

The measured results presented in the next section were generally analyzed using the analysis of variance in Table 11 with irrigation level as the main plot and CO_2 and nitrogen as subplots. Under the subplot is weeks or biweeks for repeated samplings during the season. The repeated measures were placed at this level in the hierarchy under the assumption that the sequential measurements were not truly independent replicates but were really subsamples. Some of the measurements were repeated on more than one leaf or plant within each plot, and these subsamples appear at the lowest level in the hierarchy.

For some of the measurements we questioned whether the repeated measures were being properly handled. In particular, the water relations measurements were conducted a prescribed number of days following a weekly irrigation. The irrigation would tend to reset any plant water stress back to fully hydrated followed by drying under another weather pattern. Therefore, the repeated measures under these conditions could also be considered to be independent of one another, so weeks or biweeks were also treated as a main effect as shown in Table 12, and the analyses of variance were repeated using this statistical model.

6. Plant Growth Modeling

During 1986 the means to begin developing the capability to predict the effect of possible future changes in climate and atmospheric CO_2 concentration on the growth of cotton was acquired. The hardware included a Telex 1260 microcomputer (IBM PC compatible) with math coprocessor and hard disk. A copy of the cotton growth model, GOSSYM, (IBM PC version) was obtained from the Crop Simulation Research Group at Mississippi State (Baker _et al_, 1983). They are having some success using this physiological process level model to predict cotton growth and yield under current CO_2 levels. After some initial difficulties, we now have the model running on the Telex using a Ryan-McFarland FORTRAN compiler. During 1987 we intend to change the photosynthesis equation to include CO_2 as a variable, and then to proceed make comparisons between model predictions and measured observation made during 1986 and prior years.

B. Results

1. Leaf area, flower production, boll retention, biomass, and yield

The production of biomass and yield of the cotton grown in the open-topped chambers is shown in Table 13. The response to CO_2-enrichment was most pronounced in the dry-N^+ treatment and least in the wet-N^+ with the N^- treatments in-between. Though the production of seed cotton was about 45% greater in 1986 than in 1985 in both enriched and ambient treatments, the biomass production was nearly the same. Thus, the harvest index (seed cotton/plant top weight) was greater in 1986 than 1985. This greater plant efficiency was due to a very early fruit set which limited growth of leaf and stem tissues.

A summary of the relative response of seed cotton yield to a near-doubling of CO_2 concentration for four years of experiments is given in Table 14. Under the added-nitrogen, well-watered condition the response to CO_2 was similar in 1986 to that seen in 1985 (about 50%), but less in the water stress treatment (70% compared to 104%). In both 1985 and 1986 when the drip irrigation system was used for precise water application, the CO_2 response under the water-stressed conditions was greater than under the well-watered condition.

The complex nature of components of yield in the various treatments can be seen by analyzing the time course of the boll loading (Fig. 9), which is the product of the rate of flowering (Fig. 10) and the percentage boll retention (Fig. 11). The data in Figs. 9 to 11 are averages over reps and nitrogen treatment for clarity because differences due to reps and N were small. All treatments had three periods of high boll retention. However, the wet treatments had two peaks of flowering while the dry treatments had three flowering cycles. the coincidence of high rate of flowering and high rate of boll retention by Dry C^+ during Julian 200-210 caused the boll load during that period to exceed that of Wet C^+.

Though the rate of retention was very high in the Wet C^- treatment, the rate of flowering was the controlling factor which produced an intermediate yield productivity. Dry C^- had three flowering cycles and reduced retention rates to produce the lowest yield.

Analysis of the leaf area per active boll (LA/B) on the destructive samples further clarified the character of the boll loading in the experiment (Table 15). The minimum LA/B occurred about day 175 in Wet C^+. However, the Wet C^+ remained heavily loaded per unit of leaf area until day 203 while Dry C^+ with a smaller boll load continued to produce flowers (Fig. 10) which effectively utilized the second and third periods of high retention. These analyses demonstrate the difficulty of making generalizations about the response of cotton productivity to CO_2 enrichment. The response varied during this season from a significant positive effect of CO_2 (Fig. 9, day 190) to a slight (non-significant) depression of boll load due to enrichment (Fig. 9, day 230). The flowering cycles of the treatments were completely out of phase by the end of the season. The outcome could be altered by terminating the experiment at different times. Since the length of season varies considerably across the nation and from year to year, we can

expect yield responses to future CO_2 concentrations will vary accordingly.

2. Elemental analysis of leaf time

The concentration of essential elements within leaves sampled on day 215 (3 August 1987) are shown in Table 16. With the exception of N, P, and Zn, all elements appear to be at adequate tissue levels for maximum performance. The no added N treatment (N^-) appeared to have caused N deficiency in the leaves from the well-watered (W) plots, but not in the dry water-stressed (D) plots. Deficient levels of Zn were observed in three of the four well-watered treatments. This effect is probably associated with the level of productivity of these plots, since we believe that boll loading may induce Zn deficiency.

3. Photosynthesis and stomatal conductance at chamber CO_2 concentrations

Net leaf photosynthesis and stomatal conductance were measured at midday in all of the open-top chambers on several clear days during the 1986 season using a Li-Cor Model 6000 Portable Photosynthesis System. The "Li-Cor" consists of a leaf chamber that is clamped on a leaf, and then the rate of change of CO_2 concentration in the sealed chamber is used to compute photosynthesis. Similarly the rate of change of relative humidity in the chamber along with concurrent leaf temperature measurements are used to compute stomatal conductance. The problems reported last year (Kimball et al., 1985) about high temperature instability were corrected by the manufacturer through installation of a new A-D converter, and in 1986 the system performed well even on the hottest days with the only cooling being placement of the instrument within the shade of the crop canopy. We also found, however, the instrument was more stable when set upon the ground during readings, rather than wearing the instrument using the belt supplied by the company.

The measurements were taken on three leaves in the center row of each chamber. Generally, the youngest, fully-expanded leaves were chosen for measurement. Ten observations were taken over a 20 second period and averaged by the Li-Cor software to determine the mean photosynthesis and stomatal conductance for each leaf. However, it took up to 10 seconds for the CO_2 concentration readings to begin a steady decline before actual data logging began.

The measurements were usually taken 2 days and again 6 days following the weekly irrigations. Therefore, those taken 2 days after irrigation were regarded as being unstressed for water. The weather patterns and rainfall during each week were noted and those 6-day-after-irrigation data that were obtained during weeks when the weather was mostly clear were selected for further analysis as representative of water stress conditions, particularly for the dry irrigation treatment.

The net photosynthesis results are presented in Figure 12 and Table 17. Nitrogen fertilizer did not significantly affect photosynthesis (Table 17), so the data were averaged over nitrogen as well as reps and leaves for presentation in Figure 12. Focusing on the 2-day-after-irrigation data, it is apparent that photosynthesis declined steadily through the growing season. The photosynthesis in the dry plots was close to the same as that in the wet plots, indicating full recovery from water stress after each irrigation. The data were split into mid and late season groups for analysis. CO_2 obviously had a large effect increasing photosynthetic rates about 51% in midseason and about 37% in late season.

The net photosynthesis measurements taken 6 days after irrigation exhibited considerable week to week scatter (Figure 12). As with the 2-day-after-irrigation data, there appeared to be a seasonal decline. On some of the days the photosynthesis in the dry treatments was considerably below that of the wet treatments (as expected), but not on others. CO_2 significantly increased photosynthesis an average 37% for the whole season under these water stress conditions (Table 17).

The stomatal conductance results are presented in Figure 13 and Table 18. Before mid-September, the conductances measured 2 days after irrigation were fairly similar in all the plots at about 2.5 cm/s, and then they plummeted to about 0.9 cm/s. Therefore, the data were divided into mid and late season groups for statistical analysis (Table 18). CO_2 enrichment decreased conductances by 11 and 25% for the mid and late season, respectively.

The conductances obtained 6 days after irrigation suggested a large effect of the dry treatment (Figure 13, Table 18), but the number of degrees of freedom were small for irrigation (Table 11) and the difference was not significant. CO_2 decreased conductances by an average 22% for the whole season.

4. Photosynthetic Responses to Changes in CO_2 Concentration

The methods used at midseason were identical to those used in 1985 (Kimball et al., 1985). Briefly, air at various concentrations of CO_2 was passed through the leaf chamber of an ADC portable photosynthesis system as it was clamped on numerous leaves in the center row of particular plots, and determinations of net photosynthesis were made. A LiCor LI-1600 porometer was used to measure stomatal conductance before and after the photosynthesis measurements. From these data curves of assimilation rate (A) plotted against internal CO_2 concentration (c_i) were generated. However, late in the season, the ADC portable photosynthesis system was fitted with a newly purchased DL2 Datalogger which enabled the ADC system, itself, to determine stomatal conductances as well as performing the calculations of photosynthetic rates. A boundary-layer resistance value of 0.3 $m^2 mol^{-1} s^{-1}$ (default value) was used for calculations because it produced stomatal conductance values that agreed rather well with the readings of the LiCor LI-1600 steady

state porometer. Because the porometer had been recently recalibrated at the factory, these were assumed to be accurate.

The methods of data collection did not allow more than 4 chambers to be surveyed in one day in midseason. As a result, the day of year is confounded with treatments and replications. This problem was overcome by grouping all data acquired in midseason within two days following an irrigation. Effects of water stress in the results, therefore, are solely from long-term alterations of plant performance rather than immediate water deficit, as the plants were not subjected to large water deficits during the measurements themselves.

In the late season (mid-September or later), the datalogger allowed more rapid measurements. Still, the confounding remained because the maximum number of chambers surveyed per day was only eight instead of the full sixteen. Again, data were grouped across days for analysis.

Carbon dioxide enrichment had a much smaller effect on various gas exchange parameters in midseason than in late season (Tables 19, 20). In midseason (Table 19), CO_2 enrichment decreased stomatal conductance (g_s) about 14% but had an even smaller effect (7% decrease on average) on the carboxylation efficiency or mesophyll conductance to CO_2 (CE). The compensation point for CO_2 (Γ) was unaffected, but the calculated stomatal limitation to photosynthesis (L) was greatly decreased. In the late season (Table 20), CO_2 enrichment decreased stomatal conductance by about 25% and mesophyll conductance by over 18%; both these decreases are greater than in midseason. The compensation points for CO_2 uptake was substantially lower than in midseason because of the lower temperatures, and those under CO_2 enrichment were slightly larger than those from the ambient treatment. The late-season stomatal conductance was also greatly decreased from midseason values at either CO_2 level, leading to much lower c_i's and much greater stomatal limitations to photosynthesis (Tables 19, 20). It is worth comment that in the late season, c_i's approximated those believed to be "normal" for most C_3 plants, whereas in midseason they greatly exceeded "normal" levels. We believe that this shift reflects stomatal responses to seasonally changing temperatures.

In midseason (Table 19), CO_2 enrichment produced a stimulation of photosynthesis of 69 to 74%, depending upon the particular combination of treatments. In the late season (Table 20), CO_2 enrichment stimulated photosynthesis 53 to 62% in the N-deficient treatments, but only 32 to 34% in the N-sufficient treatments. The results obtained with N-sufficient plots are consistent with results from similar experiments in 1985. As in the previous year, the lesser stimulation in the N-sufficient, CO_2-enriched plants was not due to stomata. Because CO_2 enrichment decreased the stomatal limitation to photosynthesis, differences in the effect of CO_2 must have been non-stomatal in origin. The data show an interaction of time of year and N fertility on plant photosynthetic responses to CO_2.

Representative $A(c_i)$ curves are shown in Figure 14 (midseason) and Figure 15 (late season). The trends were estimated by quadratic regressions that gave good fits. Because of the use of the datalogger in the late-season measurements, stomatal conductances were determined for each individual leaf for which photosynthesis was measured. This data set allowed an analysis of the correlation between stomatal conductance and photosynthetic capacity among individuals within a population. The analysis was done by correlating residuals, i.e., deviation of stomatal conductance from the estimated value correlated against the deviation of photosynthesis from its estimated value. This data set is unique in that photosynthetic rate estimates are corrected for variation in c_i. The estimated photosynthetic rate is taken from the population-based $A(c_i)$ curve and is calculated at the c_i of each leaf. Thus any correlations between stomatal conductance and photosynthesis in these experiments must be mediated by some agent <u>other than carbon dioxide itself</u>. Table 21 presents the R^2 values of these correlations. At ambient CO_2, correlations between stomatal conductance and photosynthetic capacity were generally poor in each of the treatment combinations (R^2 between 0.01 and 0.13). At the enriched level of CO_2, for the two well-watered (wet) treatments, the R^2 values were significant ($P=0.05$), and for the two water-stressed (dry) treatments, they were highly significant ($P=0.01$). The results indicate that there is a factor coupling photosynthetic capacity with stomatal conductance, but that in field-grown cotton the factor is effective only at enriched levels of CO_2. The degree of coupling seems to be enhanced by water stress.

5. Stomatal Response to Injected Abscisic Acid

Abscisic acid (ABA) was dissolved in a drop of ethanol and diluted with water to a concentration of 5×10^{-4} m. A mature healthy leaf was selected near the top of a plant in a chamber, and 2 μℓ of the ABA solution was injected into one of the major side veins of the leaf near its junction with the petiole. A 10-μℓ Hamilton syringe was used for the injection. Stomatal conductance of that half of the leaf was followed with time after injection, using a LiCor LI-1600 steady state porometer. The other (uninjected) half of the leaf served as a control. Because there were no trends with time in the controls, conductances here are compared to the initial reading at the time of injection. Leaf conductances were calculated as the sum of the conductances of the abaxial and adaxial surfaces.

Responsiveness to ABA was expressed as the ratio of leaf conductance 10 minutes after injection to the initial conductance (Table 22). Stomatal responses to exogenous ABA were determined on 6 days during the season. Two of the days followed the weekly irrigation by 1 or 2 days, so the plants presumably were close to full hydration; whereas, the other 4 days followed irrigation by 6 days, so presumably the plants experienced greatest water stress on those days at the end of the irrigation cycle. Analysis of the data showed that of the various main effects (CO_2, N fertility, water treatment, and time of year), only CO_2 level and day of

observation had significant effects on responsiveness to ABA. These two effects were highly significant (P=0.01). Therefore the data have been grouped by CO_2 level and day (Table 22). On the two midseason days closely following an irrigation (218 and 219), CO_2 enrichment greatly enhanced stomatal responsiveness to ABA, i.e., in the presence of CO_2-enrichment, the ABA injection caused greater stomatal closure. On the two midseason 6-day-after-irrigation days (223 and 237), stomata of the ambient-CO_2 plants were more sensitive to ABA than they had been on days 218 and 219, but CO_2 enrichment still enhanced sensitivity (Table 22). In the late season (day of year 258 and 272), there was little effect of CO_2, and the overall level of sensitivity had decreased from the earlier measurements.

These experiments provide the first field test of the presumed interaction of CO_2 and ABA on stomata, an interaction that has been previously demonstrated only in controlled environments. The data show convincingly that CO_2 enrichment enhances the effect of ABA on stomata, at least under certain circumstances. Factors causing the disappearance of this CO_2 effect are unknown, and the work may need to be repeated before it can be interpreted with confidence. We conclude only the CO_2 enrichment is capable of enhancing the effectiveness of ABA in stomatal closure.

6. Leaf Starch Content

The level of starch was determined in mature, fully-expanded cotton leaves from field-grown plants exposed to various nitrogen fertilizer and watering regimes. Leaves were sampled at sunrise and sunset by punching six 0.28 cm^2 disks with a cork borer. The same leaf was sampled in the morning and evening. These sampling times correspond to the daily maximum and minimum of starch in cotton leaves (Hendrix and Huber, 1986). The samplings were performed twice per week, 2 days and 6 days following weekly irrigations. These samples were placed in ice-cold 80% ethanol and quickly moved to a -80°C freezer for storage prior to analysis by an enzymatic technique (Hendrix and Peelen, 1987; Hendrix and Huber, 1986). Leaf samples were ground in 80% ethanol and the residue repeatedly extracted in hot (80°C) ethanol. The nonalchohol-soluble material was next digested with amyloglucosidase and the released glucose units determined by the change in absorbency due to NAD·H in a coupled glucose-6-phosphate dehydrogenase assay (Hendrix and Peelen, 1987).

To test the effect of irrigation cycle water stress on cotton leaf starch levels, leaves in the CO_2 chambers were sampled on the last day of an irrigation cycle; the leaf immediately above this leaf was sampled two days after re-irrigation. Plants were sampled in the two nitrogen treatments to determine whether this variable had any effect upon leaf starch content. As expected, the starch content of the leaves roughly doubled from sunrise to sunset each day. The greater water stress conditions experienced 6 days after irrigation compared to 2 days tended to

decrease starch levels somewhat, the change in evening starch levels from 2 to 6 days after irrigation being significantly lower in the wet treatment.

In all experiments, no effect upon leaf starch content was found in plants exposed to various nitrogen regimes (Table 23). Diminishing the amount of water applied to the plants by 1/3 (dry treatment) slightly lowered the mean starch levels in the cotton leaves for all 4 sampling conditions, but the decreases were not statistically significant (0.05). On the other hand, the elevated CO_2 within the chamber (650 ppm) more than doubled ($P = < 0.001$) the starch content in all cases: i.e., sampling either 2 or 6 days after irrigation, both in the morning and at dusk.

7. Stomatal Densities

Stomatal densities were measured on the adaxial (upper) and the abaxial (lower) sides of a single fully expanded leaf from three plants in each chamber using the leaf impression technique of Sampson (1961), with the following modification. Leaf impressions were taken using a clear, fast drying acrylic liquid (Noxell Corp., Hunt Valley, MD). The leaf impressions were taken near the center of the leaf surfaces, but did not include any major veins. Stomatal counts were made in four randomly selected light microscope fields from each impression. Each field consisted of 0.05 mm^2 at 100X magnification. Leaf impressions were taken on October 14 and 15, 1986.

The nitrogen treatment had no statistically significant effect on stomatal density of either the abaxial or adaxial leaf surfaces, or on the ratio of stomatal densities of the two leaf surfaces (Table 24). The dry irrigation treatment resulted in a significantly higher stomatal density of the adaxial leaf surfaces than the wet treatment, but had no significant effect on the stomatal density of the abaxial leaf surfaces or the ratio of the stomatal densities of the abaxial to adaxial leaf surfaces (Table 24).

Numerical differences in stomatal density did occur, however, and those factors such as high nitrogen and more frequent irrigation, which tend to increase leaf area, caused a general trend toward lower stomatal density. This result is in agreement with other research that has shown that stomatal density usually decreases as leaf area increases (Salisbury, 1927), and that the total number of stomates per leaf is somewhat constant (Gupta, 1961). CO_2 had the opposite effect. The higher CO_2 level, which might be expected to result in an increase in area per leaf (O'Leary and Knecht, 1981), resulted in significantly greater stomatal density on both the abaxial and adaxial leaf surfaces. Unfortunately, individual leaf areas were not measured in this experiment, and so we have no way to accurately estimate the total number of stomates per leaf. We suspect, however, that the total number of stomates per leaf increased in the high CO_2 treatment as has been the case with beans (O'Leary and Knecht, 1981).

There was also a larger proportionate increase in stomatal density on abaxial leaf surface in the high CO_2 treatment, such that in the high CO_2 treatment the abaxial to adaxial ratio of stomatal densities was significantly higher (Table 24). The cause of the difference in responsiveness of the abaxial and adaxial leaf surfaces to atmospheric CO_2 concentration is not known, although with other plants differences have been reported previously in response to CO_2 level (O'Leary and Knecht, 1981) and to other environmental factors (Bristow and Looi, 1968; and Lugg and Sinclair, 1979).

This preliminary examination of stomatal density in response to nitrogen, irrigation, and CO_2 levels indicates a need for further, more detailed study in order to determine how environment-induced changes in stomatal density affect basic plant processes such as photosynthesis, transpiration, and water use efficiency.

8. Leaf Temperatures

As in the three previous years (Kimball et al., 1983, 1984, 1985), foliage temperatures were measured on most cloudless days at about 13:30 MST. The results of all four years of experimentation are presented in Figure 16. The solid line and its associated equation summarize the 1983-85 results. Superimposed upon this graph are this year's findings. Once again, all wet (or well-watered) plots displayed the same general relationship, with no significant difference between the nitrogen treatments. The dry plots also showed no effect of nitrogen, as expected. They were warmer than the well-watered plots by about 1.4 and 1.1 C at ambient and 645 $\mu\ell/\ell$ CO_2, respectively. Thus, we have again confirmed that a near-doubling of CO_2 concentration increases cotton foliage temperatures about 1.0 C.

9. Leaf Water Potential, Relative Leaf Water Content, and Dry Matter Content

Two leaves per plot were sampled just before dawn and shortly after noon 2 days and six days after weekly irrigations and brought into the laboratory for determination of leaf water potential. The weekly samplings alternated between rep 1 and rep 2, so the season was divided into biweekly intervals for statistical analysis. To take the samples, a plastic Zip-loc bag was humidified with a breath of air and placed over the youngest fully expanded leaf, usually the fourth or fifth from the shoot apex, and then the petiole was severed with a razor blade. The bag was sealed and stored under a wet towel in a Styrofoam chest for transport to the laboratory. There the water potential measurements were taken using a pressure bomb.

At the same (usually) sampling times as the water potential leaves were taken, four (usually) leaf disks were punched from one side of the youngest fully-expanded leaf of another plant and placed in a glass vial for transport to the laboratory for determination of relative leaf water

content. Pre-dawn and afternoon samples were punched from separate halves of the same leaf on a particular sampling day. Once inside the laboratory, the vials plus disks were weighed for determination of fresh weight, W_f. Then the disks were floated on distilled water in covered petrie dishes within a chamber at 30°C and dim light. After 24 hours, the disks were blotted dry and quickly weighed again in the vials to determine saturated weight, W_s. The final stage was to dry the disks overnight in a convection oven followed by a final weighing to determine dry weight, W_d. Relative leaf water content, RLWC (%), was computed from: $RLWC = 100 * (W_f - W_d)/(W_s - W_d)$ In addition, the actual dry matter contents, DMC (%), were computed from: $DMC = 100 * (W_d/W_f)$.

When the data were being analyzed, it was realized that the data had more scatter than experienced previously (Kimball et al., 1985). The primary source of the increased error was traced to the vials, which adsorbed and desorbed water between the various weighing stages of the relative leaf water content determination. A second but unquantified error was leakage of soluble materials out of the leaves while floating on the water, as inferred by the growth of microorganisms in the water during the 24 hour hydration time.

The results are presented in Tables 25, 26, and 27. Soil nitrogen had no effect on leaf water status. As expected, however, deficit irrigation caused the leaves to be drier (more negative LWP, smaller RLWC, larger DMC) for all of the sampling conditions, although the differences were not always statistically significant at the 0.05 level. At no time did CO_2 enrichment significantly improve leaf water status (higher LWP or RLWC). Instead, the tendency was for drier leaves at high CO_2, particulary for the predawn samples 6 days after irrigation. The CO_2 enriched leaves had significantly higher dry matter contents (Table 27), consistent with the greater starch accumulations (Table 23).

Because CO_2 enrichment tends to close the leaf stomata (Table 18) and reduce transpiration per unit of leaf area, it is reasonable to hypothesize that high CO_2 might improve the internal water status of the leaves. However, contrary to this hypothesis and consistent with our 1985 data, these data show that increasing CO_2 caused the leaves to be drier. Apparently the larger plants growing under CO_2 enrichment deplete soil moisture as fast or faster than the ambient CO_2 plants. Therefore, the higher yields obtained with CO_2 enrichment (Table 13) were obtained in spite of an apparent worsening of leaf water status.

10. Pan Evaporation

Cumulative pan evaporation measurements were taken three days a week, 25 April through 3 October from all chambers of the CO_2 experiment. Similar to 1985, small cylindrical stainless steel pans (225 mm diameter X 110 mm high) were placed at the north end of the east walkway in each chamber. Three of the same kind of pans were also placed at the north end of each of the open-field plots for Rep I of the FIZZ/FACE experi-

ment (described in the next section) between the second and third east-most rows. An identical stainless steel pan was placed outside the NE corner of the experimental area over bare soil and adjacent to a standard U. S. Weather Bureau Class A pan (1210 mm diameter X 250 mm high). During the first week, it was observed that a few of the pans had developed tiny pinhole leaks from rust pits, so all of the small pans were coated on the inside with an asphalt roofing compound with an aluminized final coat. All the small pans were placed on stacks of concrete blocks (193 mm tall each), while the class A pan was on a wooden pallet. Blocks were added to the stacks as needed to keep the water surface areas above any shade created by the cotton canopy. An organic chlorine algacide (trichloro-s-triazinetriane) was used to retard the growth of algae, and the pans were cleaned and rinsed every 2-4 weeks. The water depths were measured from all pans using a standard Lory type C hook gauge (0.1 mm accuracy) with a specially fabricated cover that could be placed on all the small pans to provide a stable reference height. A PVC cylinder the same diameter as the small pans was placed on end in the class A pan to similarly provide a stable reference height for it.

The results are presented in Table 28 and Figures 17-19. The cumulative evaporation for the Class A pan was 1749 mm and that for the small standard pan next to it was 2311 mm. Thus, the larger surface to volume ratio of the small pan resulted in an evaporation rate that was 1.32 times larger than the Class A pan. These data are comparable to last year (Kimball et al., 1985) when the amounts were 1753 and 2193 mm for a ratio of 1.25.

Again early in the season (up to about day 180), the pans in all the experimental plots evaporated at very similar rates while the cotton canopies were small (Figures 17-19), with the open-field pans evaporating just slightly more water than the chamber pans. By the end of the season, however, the chamber pans had evaporated 1.05 times more water than the open-field pans (1516 mm compared to 1444). This latter result is contrary to the data of 1985 when the open-field pans evaporated 1.10 times more than the chamber pans.

The nitrogen fertilizer treatment had no significant effect on the pan evaporation rate (Table 28). The pan evaporation in the dry chambers was 1.03 times greater than in the wet chambers (1537 mm compared to 1494), a result which was not statistically significant and which was surprising considering that in 1985 the dry chamber pans evaporated 1.09 times as much water as the wet. An even more surprising result was that the pans in the CO_2-enriched chambers evaporated 0.94 of the amount of water from the ambient chambers (1471 mm compared to 1561), a difference that was statistically significant. This was also unlike 1985 when CO_2 treatment had no effect on pan evaporation.

The open-field pans in the FIZZ and FACE treatments evaporated 0.97 and 0.96 times as much as the control pan (1431 and 1419 mm compared to 1482). These pans were not replicated, so statistical significance could

not be tested. However, the difference is consistent with the chamber data.

The dominant mechanism that would cause the pan evaporation to be higher in the CO_2 treated chambers and field plots is unclear. We have to postulate that the larger leaf areas with CO_2 enrichment caused the humidity to be higher immediately around the pans in spite of decreased stomatal conductances. It is also conceivable that an inadvertent experimental error may have contributed. Care was taken to be sure that the height of the pans was always above the crop canopy to avoid shading by leaves. However, the greater growth of the plants in the CO_2-enriched plots often resulted in their being right at the top of the pans, whereas those in the ambient CO_2 pans were often relatively higher with respect to the tops of their plant canopies.

The small pans inside the field evaporated an average 1444 mm (Table 28) which was 0.62 times as much as the small standard pan beside the field (2311 mm). Taking into account this inside/beside the field factor of 0.62 and the ratio of 1.32 of small standard/Class A pan evaporation, the small pans in the field evaporated 0.83 times as much as the Class A pan. Additionally, accounting for the 1.05 ratio between the pans in the chamber to those outside the chamber, the small pans inside the chamber evaporated 0.87 times as much as the Class A pan, the same ratio as last year. Again, therefore, since the amount of irrigation water applied to the well-watered or wet plots was based on the Class A pan evaporation each week (Equation 9), the irrigation amount should have been on the generous side.

11. Development of Pink Bollworms

Carbon dioxide related changes may have significant effects on the damage wrought by herbivorous insects. Studies are needed to gather data to assess this problem and plan for future insect control under these conditions. Toward this end, a study was conducted on the development of pink bollworms reared on cotton grown in carbon dioxide-enriched controlled chambers and in open fields enriched with carbon dioxide by free release (FACE experiment described in detail in next section).

Four of the 16 open-top CO_2 enrichment chambers were used. Two of the chambers were those enriched with 650 $u\ell/\ell$ of CO_2 and 2 were ambient controls. Additionally, 2 of the field plots were used. One with carbon dioxide released (FACE) and the other was an ambient control. Both chambers and field plots were those that had water and nitrogen applied at rates considered to be adequate or high.

Bolls (23-28 mm and 7-12 days for CO_2 enriched plants and 10-15 days old for control plants) were each infested with 3 larvae (0-2 h old) of the pink bollworm, <u>Pectinophora gossypiella</u> (Saunders). Bolls were collected 7-10 days later and the pink bollworm larvae were allowed to

cut out of the bolls, drop into pupation containers, and pupate. Pupae were weighed 24 h after pupation and development times were calculated. Seeds were collected from the bolls and examined manually for damage. Data were analyzed by ANOVA and t tests to determine if differences existed between the treatments.

There was no significant differences in mean pupal weights of pink bollworms raised on CO_2 enriched cotton (26.80 mg, n = 125) compared to those raised on cotton not CO_2 enriched (26.24 mg, n = 89) (Table 29). In the chambers, pink bollworms had mean pupal weights of 27.11 (n = 57) and 27.57 mg (n = 24) on CO_2 enriched cotton and 27.21 (n = 46) and 26.18 mg (n = 22) on cotton not enriched. In the field plots, pink bollworms had mean pupal weights off 25.98 mg (n = 44) on CO_2 enriched cotton and 25.89 mg (n = 21) on cotton not enriched.

Likewise, there were no significant differences in mean length of development in days (newly hatched larvae to the pupal stage). On CO_2 enriched cotton in the chambers, development of pink bollworms required 21.18 (n = 57) and 21.36 (n = 25) compared to 23.59 (n = 46) and 21.32 (n = 22) days (Table 30). In the open field plots, development took longer; 27.30 (n = 46) days on CO_2 enriched cotton and 25.43 (n = 21) days on cotton not enriched. Though the difference in mean development time was not significant between CO_2 enriched cotton and cotton not enriched, the differences in mean development time between pink bollworm raised in the chambers compared to the field plots was highly significant ($P < 0.0001$). Pink bollworms raised in the chambers developed more quickly. This was probably due to higher temperatures in the chambers (2-3 °C) that increased developmental rate.

Analysis of seed damage (mean % of seeds damaged in each boll) by larvae of the pink bollworm showed no significant differences between CO_2 enriched cotton and cotton not enriched. In the chambers, damage to seeds by pink bollworm larvae was 30.93% (39 bolls examined) and 26.17% (24 bolls examined) on CO_2 enriched cotton compared to 30.45% (42 bolls examined) and 26.45% (25 bolls examined) for the ambient cotton (Table 31). In the field plots, damage to seeds by pink bollworm larvae was 45.12% (37 bolls examined) with CO_2 enrichment compared to 39.51% (24 bolls examined). The differences in mean % seed damage between chambers and field plots was highly significant ($P < 0.001$). The longer developmental times for larvae in the field plots (Table 30) probably allowed the larvae access to more seeds and resulted in more damage to seeds in field plots.

There were no significant differences ($P > 0.05$) in the C:N ratios between CO_2 enriched cotton and ambient CO_2 cotton for either immature seed, mature seed from chamber-grown cotton, or mature seed from FACE-grown cotton (Table 32). The C:N ratios, for mature seed from cotton grown in the chambers (9.83 for CO_2-enriched cotton and 11.03 for ambient CO_2 cotton), were significantly lower ($P < 0.05$) than the C:N ratios for immature seed from chamber-grown cotton or for mature seed

from FACE-grown cotton (Table 32). Mature seed from cotton grown in the chambers had significantly ($P < 0.01$) more nitrogen (4.59 and 4.30% for CO_2-enriched cotton and ambient CO_2 cotton, respectively) than either immature seed from chamber-grown cotton or mature seed from the FACE-grown cotton (Table 32).

These findings indicate that the pink bollworm, mostly a seed-feeding insect pest on cotton in mid and late season, will show little change in its developmental parameters during this part of the growing season as a result of increases in atmospheric carbon dioxide, i.e., the moth itself is not likely to be affected. These findings differ from 3 earlier studies (Osbrink et al., 1987; Lincoln et al., 1986; Lincoln et al., 1984), that examined the effects of carbon dioxide enriched plants on insect development. The earlier studies were done on foliage-feeding caterpillars, two on the soybean looper on soybeans and one on the cabbage looper on lima beans. These studies showed that C/N ratios increased in leaves of C_3 photosynthetic plants as CO_2 increased and that leaf feeding by the looper caterpillars increased to compensate for lesser N_2 intake. This resulted in pupae that weighed significantly less in the cabbage looper study and larvae that tended to weigh less in the soybean looper studies. The net effect was less efficient feeding despite more leaf consumed. In our study, there was no significant difference in the C/N ratios of the seeds from ambient and CO_2-enriched cotton plants. Thus our findings do not conflict with the earlier studies. Though developmental parameters alone do not determine population levels of an insect, they certainly are important factors. Therefore, it is likely that population levels of the pink bollworm will be less affected than populations of foliage-feeding insects by increased atmospheric CO_2. However, population studies will be required to actually know what the impact of increased CO_2 will be. Through this project, there has been one study on population levels (Butler et al., 1986). That was on the sweet potato whitefly on CO_2-enriched cotton and no differences were reported. The whitefly is a phloem feeding and the C/N ratio of the phloem was probably not affected. We would expect similar results with the pink bollworm in terms of population levels.

Additionally, other parameters should be considered that might influence populations of pink bollworms raised on CO_2-enriched cotton. Some of these include: 1) examining pollen for changes in nutritive value, ie., C:N ratio; this is important since the larvae of early season generations of pink bollworms sustain themselves on cotton flowers (squares) until bolls are available; factors that impact on the pink bollworm population early in the season significantly affect the population levels that occur in mid and late season; 2) determining if the more rapid growth rate of the bolls of CO_2-enriched cotton reduce the time in which the bolls are susceptible to pink bollworm infestation; our observations in the 1986 season indicate that this is likely to be true; and 3) determining the affect on the pink bollworm population of the availability of more bolls on CO_2-enriched cotton; this is important since boll availability may be limiting early in the season and again later as the cotton approaches "cut out".

Also, the beet armyworm, a western cotton pest and a leaf feeder, will be considered for possible use in CO_2-enriched cotton experiments during the 1987 season. This would permit verification of the C/N ratio concept for cotton and expand it beyond leguminous plants.

12. Soil Atmosphere CO_2 Concentration and Pressure Gradients

The 1985 soil carbon dioxide data were further analyzed to determine the variation of CO_2 concentration with time during the year for a specific depth (Figure 20). The largest difference in CO_2 concentration was present at the 0.6 m depth. The explanation for the CO_2 concentrations becoming similar inside and outside the chamber after the blower was turned off has become clearer. In this situation, the natural decrease in CO_2 production with the lowering of biological activity in the fall played a more important role than the diffusion of CO_2 from the higher to lower partial pressures in bringing the two curves together.

A similar experiment was conducted in 1986 as in 1985, but included sampling depths at 0.8 and 1.0 m. Also, additional sampling sites were located at distances of 0.2, 0.6 and 1.2 m outside the chamber wall compared to only one at 2.5 m (designated as the "no-chamber" site) for the 1985 experiment. Chamber blowers were started on 26 April and turned off on 10 October 1986. The profile distributions of CO_2 with depth for the "dry" and "wet" treatments on various days during the year are presented in Figure 21. There was some decrease in CO_2 concentration 0.6 m from the chamber compared to 1.2 m, so it is possible some decrease occurred even at 1.2 m. Differences in CO_2 distribution were exhibited between the two irrigation treatments, with the concentration values in the dry chamber lower than the ones in the wet and with the lowest concentrations occurring closest to the chamber walls. For the dry treatment in particular, soil CO_2 concentrations at the deepest depth of 1 m was almost equal to that observed at the .05 m depth. Greater biological CO_2 production activity in the wet than dry caused a different distribution pattern. Also, the higher water content would decrease mass flow and diffusion of CO_2.

Time sequences of CO_2 concentration for the dry treatment are illustrated in Figures 22 and 23 for the 0.05 to 0.4 m and 0.6 to 1.0 m depths, respectively. Again as in the 1985 results, CO_2 concentration differences inside and outside the chambers were larger at the deeper depths in the soil compared to the shallower depths.

Differential pressure measurements were made inside and outside the chamber while the blower was on and off to determine whether a pressure factor was involved in the CO_2 concentration differences observed in the soil profile for the two different locations. Pressure samplings were taken at the soil surface and 0.1 m below. Pressure (Figures 24 and 25) differentials were greatest close to the air manifold outlet (shown as large circles) and also close to the chamber wall. Negative pressure differentials were also present and occurred midway between the air

distribution manifolds. While the pressure differences appear low, continuous imposition of such a condition could be responsible for the flushing out and replacement of soil gases with that of atmospheric composition. This explanation is a very crude qualitative picture of what is happening in the chamber and more detailed measurements and application of diffusion and mass flow movement of gases is necessary.

While large differences in soil CO_2 concentration have been observed between inside and outside the chambers, no significant differences have been observed between chambers. Large consistent increases in cotton growth have been observed with increasing atmospheric CO_2 concentration in the chambers while differences in cotton growth between ambient chambers and open-field plots have been minor and inconsistent (Kimball et al., 1983, 1984, 1985), so therefore, it seems unlikely that these large decreases in soil CO_2 concentration in the chambers has had any significant effect on cotton growth.

13. Aerodynamic Resistance

The air movement within an open-top chamber is different from that outside. The fans provide a continuous flow of air upward at an average velocity of about 0.13 m/s (4 air changes per minute, Kimball et al., 1983). The walls provide a windbreak, yet outside air does penetrate the open top with the amount increasing with increasing levels of outside wind speed and air turbulence. To determine how the aerodynamic resistance to water vapor (or CO_2) transport was changed by the chambers, measurements of this parameter were made using the blotter paper leaf approach.

The blotter paper "cotton plant" was constructed using 2 sizes of wooden dowels and wire for main stem, lateral branches, and petioles. The "leaves" were cut from green blotter paper using a pattern based on an actual cotton leaf. The finished plant had 32 leaves with a total area of 0.1822 m2 and a height of 0.6 m, slightly less than the height of the cotton canopy on 12 August 1986 when the measurements were taken. The procedure was to wet the "plant" outside the cabin by the field using a spray bottle and then weigh the plant on a balance inside the cabin. Then quickly, the plant was carried to the field and placed in a gap in the canopy of the IIW2 chamber (Figure 1) or just to the north of it in the open field. After about 7 minutes the "plant" was again quickly carried back into the cabin for reweighing to determine the amount of water evaporated. While the blotter paper plant was in position in the plant row, "leaf" temperatures were measured continually on individual leaves of the plant rotating from sunlit leaves at the top to shaded leaves below. Air dry and wet bulb temperatures were measured between the plant rows near the top of the canopy close to the artificial plant using an Assmann psychrometer. Windspeed at the weather mast (Gill propeller anemometer, 2.5 m height) was manually recorded from the display of the data acquisition system during each evaporation run. Using average leaf temperature to compute the saturation vapor pressure at the

surface of the blotter paper, aerodynamic resistances were calculated for several evaporation runs.

The aerodynamic resistances are plotted in Figure 26 as a function of windspeed. The resistances outside the chamber averaged about 45 s/m, while those inside were somewhat higher at about 60 s/m. There did not appear to be any dependence on windspeed within the chamber. Also plotted in Figure 26 are some empirical curves found by van Bavel and Ehrler (1968) for sorghum. The above canopy curve is considered to be the resistance to gas exchange by the air above the top of the crop canopy and the within-canopy curve represents resistance to gas exchange by the air within the canopy, while the total curve is the sum of the two. These data tend to be lower than what they found, which is surprising because cotton generally has a tighter canopy. However, there was still some open space between rows, so it was not entirely closed on the day of these measurements. These data do indicate, however, that the resistance is about 1/3 higher inside the chambers than outside.

FIZZ/FACE EXPERIMENT

A. Materials and Methods

1. Overall design, plot plan, and culture of culture of experimental crop

This experiment involved the application of CO_2 to cotton in an open field, as mentioned earlier. The first method was to irrigate the cotton crop with carbonated (FIZZ) water, and the second was to release gaseous CO_2 from tubing at the base of the plants, a free-air CO_2 enrichment (FACE) experiment. A plot plan is shown in Figure 27. There were four replicates each of the control (C), fizz (Z), and free-air (A) release plots. The basic plot areas were 5 rows (40 inch, 1.016 m spacing), 5 m long, as indicated in Figure 27. The control and fizz plants were planted in strips 8 rows wide, so there were two border rows on one side and 1 on the other. There were at least 2 m of border at the end of each C and Z plot. The tubing for the A plots was laid along a 20 m length of 20 rows at the base of the plants. Thus there was a 7 m border around each of the A plots that was enriched with CO_2, as indicated by the dashed lines. A minimum 7 m spacing was also used between the edge of an A border and an adjacent C or Z plot to diminish CO_2 carry-over from the A to the C and Z plots. The numerous smaller rectangular plots in the Figure were part of an unrelated cotton breeding program.

A weather mast was installed midway between the C and Z plots of rep 1 (Figure 27). At the top at a height of 2.5 m was a Gill propeller-vane anemometer for measuring wind speed and direction. Horizontal solar radiation was measured with a Spectran pyranometer (Model 4048) on a south-pointing arm of the mast at a height of 2.0 m. Duplicate

aspirated ceramic-wick psychrometers were mounted at the 1.3 m height to measure air dry and wet bulb temperatures. (This height was close to the height of the psychrometers in the open-top chambers described in the previous section.)

2. FIZZ/irrigation System Design and CO_2/Water Use

The irrigation system for the FIZZ/FACE plots is shown schematically in Figure 28. The FACE (A) and control (C) plots in each rep were irrigated together, and each rep was irrigated in sequence during 6 days of the week. (The open-top chamber plots received their weekly irrigation on the 7th day.) All 4 FIZZ plots were irrigated together 6 mornings of the week, generally starting about 8 am. The amount of water applied was measured using duplicate in-line water meters, and the daily irrigation times were controlled from time clocks and solenoid valves. The water pipes carrying the water to the field and the manifold of tees were PVC of 1 1/2 inch diameter, sufficiently large that pressure losses from one end of a manifold to the other were negligible. The drip irrigation tubing was "Netafim" from Aquanova with 1 liter/hr (at 10 m of head) emitters spaced 0.3048 m apart. The tubing was laid at the base of the plants along each row.

The irrigation and rain amounts are presented in Table 33. The first irrigation was applied by flooding and the 150 mm is only an estimate of the amount applied. The FIZZ machine was not fully operational until 2 July, so before that time the FIZZ plots were irrigated together with the other plots. The irrigation amounts were the basically the same as the well-watered treatment of the CO2/WATER/NITROGEN experiment. That is, each week the Class A pan evaporation from the past week and the leaf area projected from the past week's plant harvests were used in Equation 1 to calculate a weekly amount of water to apply. This weekly amount of water was divided by 6 to determine the amount of water to apply each of the next 6 days. Corrections were made in the target amount to apply each week for the excess or shortage actually applied the previous week and also for rainfall. The total amount of water applied over the whole season of 1358 mm (averaged over all the plots, Table 33) is very close to the amount given the well-watered treatment in the open-top chambers (Table 7), as intended.

CO_2 was injected into the irrigation water using a commercial carbonator ("FIZZ machine") from Carboflow, Inc., Phoenix, AZ, similar but larger than the ones they market for carbonating drinking water for chickens. The CO_2 was supplied from the same liquid bulk tank used for the open-top chamber enrichment (Kimball et al., 1983). The pressure was reduced to about 550 kPa through a regulator, and then connected to the carbonator. The CO_2 flow rate was about 34 liters/min (STP,1.1 g/s) when the FIZZ plots were being irrigated. This CO_2 use rate supersaturated the water with CO_2 to about 2.3 g/liter at emergence from the drip irrigation emitters. (Deionized water can dissolve about 1.5 g CO_2/liter.) Hissing and effervescence at the emitters were further evidence that the

water was supersaturated. Dividing by the total FIZZ plot area of 361 m^2 into the CO_2 flow rate, the CO_2 release rate per unit area was 3.1 mg m^{-2} s^{-1}. Multiplying by the total CO_2 application time of 292 hr (Table 33), the total amount of CO_2 used in the FIZZ plots was 3.25 kg/m^2.

3. FACE system design and CO_2 use

The free-air CO_2 enrichment FACE experiment was designed around the concept of using drip irrigation tubing to dispense the CO_2 at the base of the plants. Therefore, some preliminary measurements were done to determine the CO_2 flow characteristics of drip irrigation emitters. A length of irrigation tubing containing 30 emitters was connected to pure CO_2 through a regulator and valve. A mercury manometer was used to measure the pressure in the line. Flow rates from individual emitters were measured by inverting a water-filled graduated cylinder over each emitter in a shallow pan of water, and then using a stop watch to determine the rate at which the CO_2 bubbles filled the cylinder.

The emitters tested were Aquanova "netafim" tortuous path type rated at 1 and 2 liters of water per hour (at 10 m of head). These emitters were the same as those used for the actual irrigation systems of the FIZZ/FACE and CO_2/WATER/NITROGEN experiments, respectively. As shown in Figure 29, both emitters had excellent discharge characteristics from the standpoint that it was possible to design a uniform distribution system with most of the pressure drop occurring across the emitters and very little along the distribution tubes. Since better uniformity could be achieved using 1 l/hr emitters, they were was selected for use.

A schematic diagram of the FACE distribution system is shown in Figure 30. CO_2 from the main liquid storage tank is passed through a first stage regulator to decrease the pressure from about 2 MPa to 500 kPa. Then it passed through a main solenoid valve to a manifold with replicate second stage regulators, flow meters and valves. These were connected in turn to pipes which carried the CO_2 to manifolds in the field. The large (1 1/2inch) diameter made pressure drops across the field negligible, as was determined using a mercury manometer. Flow rate checks of individual emitters all around the field using an inverted water-filled cylinder and a stop watch confirmed that the CO_2 was being dispensed uniformly. Separate tubing was used to dispense the CO_2 from that used to apply the irrigation water. This was done for convenience since some irrigation had to be done at the same time as CO_2 enrichment. However, some tests were done that showed that CO_2 could be released uniformly from tubing that had just previously been filled with irrigation water.

A Matheson Model 8100 mass flow meter was inserted into each line in turn while all were flowing to calibrate the in-line rotameter flow meters and to allow setting of the regulators and valves to produce a 120 liter/min (STP) flow rate. This flow rate applied to each 406 m^2 FACE plot area produced a CO_2 release rate of 10 mg m^{-2} s^{-1}. The sole-

noid valve was controlled by a time clock set to turn on the CO_2 at 06:00 each morning and turn it off at 17:00 for 11 hours of enrichment each day. The enrichment started on 16 June when the crop canopy was fairly developed, and it continued until 29 September. Multiplying the total time by the release rate, the total CO_2 use was 42 kg/m^2.

A sampling system was constructed to measure the CO_2 concentration in the air of all the FACE, FIZZ, and control plots. The basic design was the same as used for sampling the air in the open-top chambers (Kimball et al., 1983). Briefly, sampling pumps and air intake manifolds were mounted out in the field. They pumped sample air continuously into the instrument cabin through 6.4 mm O.D. polyethylene tubing. An Omnidata Model 516 Polycorder computer with a "home made" interface was used to sequentially select the various sampling lines for analysis by turning on solenoid valves to route the sample through a Beckman Model 865 infrared CO_2 analyzer. A 30 second wait was inserted between switching samples, and then after the analyzer was settled on the new sample gas, a measurement of CO_2 concentration was made. The CO_2 concentration values were stored temporarily in the Polycorder and eventually transmitted to the main laboratory computer for further processing.

Sampling manifolds were mounted in every plot at 75% of plant height. In addition, in Rep 4 (Figure 27) vertical CO_2 profiles using additional manifolds at the 25 and 50 % plant heights and at 1.8 m above the soil surface. The heights of the manifolds were adjusted weekly as the crop grew (except those at 1.8 m). The manifolds were oriented diagonally across the center row of each plot, so that one end of the 3-m-long manifolds was midway between rows and the other end was midway between rows on the other side of the center row. Thus, the air was sampled both between and within rows. The sampling pumps were the same reliable Dayton Speedaire oil-less diaphragm pumps used also for the CO_2/WATER/NITROGEN experiment, as mentioned earlier. They were rated at 24 liter/min at 70 kPa. A Matheson mass flow meter was inserted into the longest sampling line (about 130 m),and the measured air flow was 12.8 liters/min (STP). Some response time tests were made by moving the pump intake quickly into and out of a CO_2-enriched chamber. About 19 seconds were required for the first detection of the CO_2 change and then another 12 s for a 50 % signal change. Thus, CO_2 fluctuations faster than about 1 cycle/48 seconds were damped by the sampling system.

4. Soil pH and Carbon Dioxide Concentrations

The manner in which the carbonated (FIZZ) water affected the pH of the irrigation water and of the soil was determined at various times following trickle irrigations with the carbonated water. The pH of the Fizz water collected from the emitter was determined with a temperature-compensated glass electrode. The pH of the moist soil where the irrigation water dripped into the soil was also determined.

The irrigation water pH was lowered from 7.5 to 5.1 by the CO_2 gas saturation treatment (Table 34). This carbonated water, when supplied

to the field, lowered the soil pH by approximately 1.5 units. For this example of Table 34, carbonated water was applied from 0830 to 1300. When the irrigation stopped, the soil pH gradually increased and reverted back close to the check soil pH overnight.

Soil CO_2 concentrations were determined at various depths in the soil profile using the method of gas sampling with specially prepared hypodermic needles, as described previously (Kimball et al., 1984, 1985).

The CO_2 concentration in the soil profile was also affected by the carbonated water treatment as illustrated by a comparison of Figure 31 of the check and Figure 32 of the treated plot. A rapid increase in CO_2 amounts was evident soon after the irrigation treatment was started at 0830 at the 0.05 and 0.1 meter depths. While a similar dramatic increase was not observed at the 0.2, 0.4, and 0.6 meter depths in the carbonated water treatment, the CO_2 concentration was higher in the treated than untreated at the respective depths, indicating that the carbonated water and/or CO_2 gas could move downward into the deeper depths, and that the plants experienced an altered soil gas, soil-pH environment in the treated compared to the untreated plot. These pH and soil CO_2 concentration changes were similar to those observed previously by Nakayama and Bucks (1980) who used a subsurface trickle irrigation system to also irrigate with carbonated water.

5. Atmospheric CO_2 Concentrations

The CO_2 concentration of the air in the various plots of the FIZZ/FACE experiment are presented in Tables 35-36 and Figures 33-37. The mean CO_2 concentrations at the 75% plant height from 21 June through 28 September is presented in Table 35 for all the reps and treatments. The mean daytime CO_2 concentration in the control plots was 360 μℓ/ℓ and just slightly higher in the FIZZ plots at 364 μℓ/ℓ. As hoped, however, the release of the gaseous CO_2 at the base of the plants in the FACE plots produced an average daytime CO_2 concentration of 522 μℓ/ℓ, a very respectable enrichment level. The diurnal course of the CO_2 concentrations at the 75% plant height are illustrated in Figure 33. The control and FIZZ concentration curves fall almost on one another, and they both decline during the daytime. The most dramatic feature of the graph is the sudden increase to over 800 μℓ/ℓ in the FACE plots after the CO_2 is first turned on in the morning, while the wind speed was generally calm (upper part of Figure 33). Later in the afternoon when wind speeds were higher, the concentration was about 500 μℓ/ℓ. Also shown are the standard deviations of the individual CO_2 observations. Whereas the control or ambient concentrations deviated about 60 μℓ/ℓ throughout the day, the standard deviations of the FACE concentrations varied from about 350 μℓ/ℓ just after dawn to about 100 μℓ/ℓ at the afternoon minimum.

The mean CO_2 concentrations at the various heights in Rep 4 are presented in Table 36. At 1.8 m the daytime CO_2 concentration was

increased slightly (about 12 μℓ/ℓ) above the control. Close to the base of the canopy at the 25% plant height, however, the concentration was about doubled to 700 μℓ/ℓ. The diurnal course of these concentrations is shown in Figures 34-36. In Figure 34 for the control plot, the curves for the various heights almost fall on top of one another showing that the vertical variation of CO_2 concentration is very small, at least on the scale employed by this graph. In Figure 35 for the FIZZ plot, the CO_2 concentration at the 25% height is shown to increase a little above that above the crop during the daytime. Figure 36 for the FACE plot is much more dramatic. The concentration at the 25% plant height was increased considerably above that at the 1.8 m height for most of the daytime. Early in the morning while the wind was calm, the CO_2 concentration averaged more than 1400 μℓ/ℓ decreasing to about 600 μℓ/ℓ in the afternoon when the atmosphere was more turbulent. Vertical profiles of CO_2 concentration are shown in Figure 37 for observations made during the hours ending at 7 am and 1 pm. At 7 am the FACE release had started, but not the FIZZ. The FIZZ and control profiles were essentially identical at this time, as expected. This plot does illustrate the strong inverse CO_2 gradient of the FACE plot under these calm early morning conditions, which is the worst case time of this phenomena. Perhaps we should have delayed release of the CO_2 by an hour. At 1 pm there was a slight increase in CO_2 concentration above the control in the FIZZ plot. The FACE plot shows enrichment ranging from about 100 μℓ/ℓ at the 75% height to 250 μℓ/ℓ at the 25% height. Thus, although these inverse gradients are not desirable from the standpoint of simulating what the future atmosphere will be like, nevertheless by frequent sampling, the actual mean concentrations are well-defined, and from models of the most active photosynthetic height, it should be possible to define a single effective concentration from data such as these.

The effect of wind speed on the CO_2 concentration is further illustrated in Figure 38 where CO_2 concentration at the 75% plant height in the FACE plots is plotted against wind speed on several days selected because they represented a wide range of wind speed. At low wind speeds, there was much variability in CO_2 concentration, and enrichment levels were high. Conversely, at higher wind speed the constant release rate resulted in rather low CO_2 concentrations. Using these data, it should be possible to construct a first level of active control of CO_2 concentration. Wind speed could be used as an input to a CO_2 flow controller to change the release rate to achieve more constant levels of enrichment, rather than merely using a constanst release rate and sampling to see what was the resultant enrichment, as we have done.

B. Results

1. Leaf Area, Flower Production, Boll Retention, Biomass and Yield

The production of biomass and yield of the plots in the FIZZ/FACE experiment is shown in Table 37. Averaging over the 4 replicates, the FIZZ and FACE treatments increased biomass production by 2 and 17%,

respectively. Total seed cotton production was increased by only 1 and 9%, respectively.

One reason for the apparent small response to the treatments was the astonishingly high productivity of the Replicate II control (C) plot (Table 37). This plot had a yield almost 50% greater than any of the other control plots. It had the highest yield of any replication of any treatment. Because this plot seemed to have been unusual for some reason, the data have also been analyzed using only three control plots (Table 38).

As shown by the boll loading graph (Figure 39), the treatments had greatest divergence during August (day 200-230). This is reflected in the fact that open bolls on the day of final harvest (Oct. 2) showed a 17% and 42% increase due to the FIZZ and FACE treatments, respectively, for three replications. When the estimated weight of green bolls was added to the production, the advantage of the FIZZ and FACE treatments was reduced to 11% and 22% respectively.

The components of yield are presented in Figures 40-41 and Table 39. The seasonal pattern of boll loading (bolls/m^2d) for the FIZZ/FACE experiment is presented in Figure 39. The cotton in the free-air CO_2-enriched (FACE or A) plots had more rapid boll loading from day 185 to 200, as shown in Figure 39. The duration of this initial flush of flowering was nearly 20 days longer in the FACE plots compared to the control plots (Figure 40), so that rate of flowering remained high during a time of moderate (50%) retention rates (Figure 41). However, the heavy boll load suppressed the late season flush of flowering in the FACE plots (Figure 40), and the control (C) and FIZZ plots had a late fruit set and a seasonal yield that was similar to the FACE treatment.

Irrigation with CO_2-saturated (fizz) water produced intermediate flowering and boll loading patterns between those of the control and FACE treatments. Whether this was due to the effects on roots as suggested by Mauney and Hendrix (1987) or due to the slight increase in CO_2 detected in the canopy atmosphere (Tables 35 and 36) cannot be stated at this time.

The leaf area index (LAI) and the leaf area per active boll ratio (LA/B) for these treatments are shown in Table 39. The minimum LA/B occurred two weeks later in these field plots than in the open-topped chambers nearby. The greater leaf area in the FACE plots carried the higher boll load until about day 230. Regrowth of leaf area in the control (primarily Rep II) plots after day 240 produced the heavy second phase of boll loading of that treatment which was not matched in the FIZZ and FACE plots. As in the open-topped chambers, the dynamics of flowering and boll loading caused the plots to be out of synchronism. This resulted in seasonal productivity which showed little effect of the treatments (Table 37), though the effect on early production was significant.

2. Elemental Analysis of Leaf Tissue

Concentration of the essential elements in leaf tissue in these plants on day 215 are shown in Table 16. All treatments appeared to be N and Zn deficient. These deficiencies may have influenced the performance of the crop in reaction to CO_2 enrichment, particularly during late season (after day 215) when the treatments seemed to converge in total productivity.

3. Photosynthesis and Stomatal Conductance

Net photosynthesis and stomatal conductance measurements were taken in the FIZZ/FACE experiment using a Li-Cor 6000 portable photosynthesis system. The measurements were taken weekly, usually on Thursday depending on sky conditions. As in the CO_2/WATER/NITROGEN experiment described previously, the measurements were taken near midday on three leaves per plot choosing the youngest, fully-expanded leaves for measurement. Ten observations were taken over a 20 second period and averaged by the Li-Cor software to determine the mean photosynthesis and stomatal conductance for each leaf.

The net photosynthesis results are presented in Figure 42 and Table 40. Figure 42 shows that photosynthesis started at about 30 μmol m^{-2} s^{-1}, on day 177 (26 June) and declined through the season to less than 20 μmol $m^{-2}s^{-1}$, similar to the well-watered cotton in the open-top chambers (Figure 12). The photosynthetic rates in the FACE plots generally were slightly higher than those in the control or FIZZ plots, whereas neither the FIZZ nor the control plots were consistently higher than each other. Because there was a sharp drop in stomatal conductance after 10 Sep (day 253, discussed shortly), the photosynthesis data were broken into "before 10 Sep" and "after 10 Sep" in Table 40, which shows that the mean photosynthetic rate before 10 Sep in the FACE plots (25.7 μmol $m^{-2}s^{-1}$) was a statistically significant (0.05) 9% higher than that of the control plots (23.6 μmol $m^{-2}s^{-1}$). It was higher after 10 Sep also, but the difference was not statistically significant.

Figure 43 shows the stomatal conductance results, which were near 2.5 cm/s most of the season and then dropped to about 1 cm/s after about day 253 (10 Sep). During August (days 213 to 243), the conductances in the FACE plots were consistently below those of the control and FIZZ plots, but otherwise there do not appear to be any consistent differences. The mean conductances for each treatment before and after 10 Sep are presented in Table 40. The mean FACE conductance before 10 Sep of 2.43 cm/s was significantly (0.05) below that of the FIZZ plots (2.79 cm/s), but not the control plots (2.70 cm/s). No differences were significant after 10 Sep, but again conductances in all treatments were much below their values earlier in the season, probably because of temperature influences on stomatal conductance.

Thus, the higher CO_2 concentration in the plant canopy from the FACE treatment (Table 35) apparently increased photosynthetic rates by about

9%, which is considerably smaller than the biomass increase of about 33% (Table 38). At the same time the elevated CO_2 slightly but significantly decreased stomatal conductances. The photosynthetic rates in the Rep 2 - control plot were similar to those in the other Reps, so the greater growth and yield in this plot (Table 37) cannot be attributed to abnormal leaf photosynthesis. The carbonated irrigation water of the FIZZ treatment did not detectably increase photosynthetic rates, so the greater growth and yield in this treatment (Tables 37, 38) also probably must be attributed to some other cause.

4. Leaf Starch Content

Leaves were sampled from the FIZZ/FACE plots and analyzed for starch content using sampling and analysis procedures described previously for the CO_2/WATER/NITROGEN experiment, except the sampling was done only once per week on these daily irrigated plots. The leaves exposed to elevated atmospheric CO_2 (FACE) contained, on the average, 40.3% higher starch than controls in samples collected at dusk. Samples taken at dawn from this experiment contained an average of 42.8% higher starch than control leaves. Both dawn and dusk samples taken from leaves of plants irrigated with CO_2-saturated water in this field (FIZZ) had starch levels which were not statistically different from those of the control plants.

5. Leaf water potential, relative leaf water content, and dry matter content.

At the same time that leaf samples were taken from the CO_2/WATER/NITROGEN experiment plots, they were also taken from the FIZZ/FACE experiment plots for analysis of leaf water potential, relative leaf water content, and dry matter content. Sampling and measurement procedures were the same, except that 1 rather than 2 leaves were taken per plot for the leaf water potential measurements.

The results are presented in Table 42. The plots in this experiment were irrigated daily (except Tuesdays) with applications intended to make them well-watered. And indeed, all these measurements of plant water status are similar to those from the wet, 2-day-after-irrigation treatment of the CO_2/WATER/NITROGEN experiment (Tables 25, 26, and 27). Thus, as expected, neither the FIZZ nor the FACE treatment of this experiment affected the leaf water status of these well-watered cotton plants (Table 42).

CO_2-TEMPERATURE INTERACTION EXPERIMENT

The increasing atmospheric CO_2 concentration is predicted by climate modelers to lead to a significant warming of the earth's climate. The direct effects on plant growth were addressed in the CO_2/WATER/NITROGEN and FIZZ/FACE experiments, but if these climate warming predictions prove accurate, then any interaction effects between temperature and CO_2 on plant growth could be very important.

A. Prior Work

In two comprehensive reviews of the effects of atmospheric CO_2 enrichment on plant productivity under normal light and temperature conditions, Kimball (1983) found that an approximate 330 to 660 ppm doubling of the air's CO_2 content led to an approximate one-third increase in crop yield, or that a 300 ppm increase in atmospheric CO_2 concentration enhanced plant productivity by a factor of 1.30. In two subsequent reviews, Cure (1985) and Kimball (1986) looked at the interactive effect of air temperature variability upon this relationship. Cure found some evidence to suggest that relative increases in plant growth due to atmospheric CO_2 enrichment were generally greater at higher temperatures. Kimball, on the other hand, found a plot of the relevant data to be extremely scattered and devoid of any significant trend. Consequently, he concluded that atmospheric CO_2 enrichment "stimulates growth by roughly the same relative amount over the (temperature) range at which plants can normally be grown."

It is very possible, however, that a strong temperature effect on Kimball's mean CO_2-productivity relationship (1983) could easily have been missed by these reviews and the primary work upon which they were based, for the following reasons. First, most of the studies reviewed by Cure and Kimball were not designed to reveal the existence of a temperature effect of the nature here postulated. Consequently, the temperature range within which the great bulk of the experiments were conducted was--for obvious reasons--that range at which plants are normally grown. And that temperature range may not have been sufficient to reveal the presence of a significant temperature effect, particularly in view of the great variability that is generally associated with agronomic and horticultural experiments of the type in question.

A second reason why a real temperature effect may not have been detected in prior studies derives from the fact that most experiments with crops stretch over the entire period of the year that they can safely be grown. As a result, not only are few data points obtained for different temperatures, but those data points which are obtained are reflections of the whole range of temperature conditions which prevailed over the entire life of the crop. Thus, specific temperature effects at specific stages of crop growth are continuously integrated (and, hence, somewhat disguised) during the development of the crop's final yield.

B. New Experiments

In an attempt to overcome the shortcomings of experiments of the type just described, we decided to grow a number of plants year-round at Phoenix, Arizona, where the seasonal extremes of temperature experienced by the plants would push them to the limits of their thermal tolerance at both the hot and cold ends of the temperature spectrum. In addition, we were determined to conduct the experiments in such a way that we would obtain <u>weekly</u> values of plant growth, thereby obtaining many data points over the widest possible range of temperatures.

The plants which we selected for study were carrot (Daucus carota L. var. sativus cv. Red Cored Chantenay), radish (Raphanus sativa L. cv. Cherry Belle), water hyacinth (Eichhornia crassipes (Mart.) Solms), and water fern (Azolla pinnata var. pinnata). All four species were grown in open-top, clear-plastic-wall, CO_2 enrichment chambers maintained out-of-doors. These chambers and their CO_2 supply, distribution and monitoring systems were similar to those used in the CO_2/WATER/NITROGEN experiment. Suffice it to say here that half of the chambers were always maintained at ambient CO_2 concentrations (about 340 ppm), while the other half were continuously maintained at elevated concentrations which averaged about 640 ppm.

Within these chambers, the carrots and radishes were grown from seed in a rooting medium composed of 50 percent Sunshine Mix Complete No. 1 (Fisions Western Corp., Vancouver, B.C.) and 50 percent medium-sized vermiculite. Seeds were sown in a number of 17-liter plastic pots in sufficient quantities to allow weekly destructive harvests ranging from 400 plants per species at the beginning of each growth cycle to about 40 plants per species at each growth cycle's conclusion, the first cycles of which were begun in September of 1985. Daily watering with deionized water kept water stress at a minimum and provided no additional fertilization. Total per-plant dry-weight increases per week were determined for each CO_2 treatment and ratioed (640 ppm/340 ppm) to yield a corresponding "growth modification factor," which we plotted each week as a function of the mean air temperature of the current week and the preceding week (to allow for the possibility of some degree of acclimation). The air temperatures used for this purpose were obtained from hourly measurements made in each chamber with shielded, aspirated thermocouples.

Within the same chambers, floating mats of water ferns were grown in 570-liter sunken metal stock tanks, either coated on the inside with silicone sealant or lined with clear polyethylene to prevent unwanted contamination of the water by metallic corrosion products. Growth cycles of these plants, the first one of which was also begun in September of 1985, were initiated by introducing 200 grams (on a fresh or wet-weight basis) of the plants into deionized water supplied with the nutrient medium described by Reddy and DeBusk (1985)--but devoid of any nitrogen. Subsequently, once a week the plants were removed from their holding tanks by raising normally-submerged circular nylon screens, which would catch and rigidly support all of the water fern plants in each tank. The entire water fern mats, resting essentially undisturbed on these screens, would then be taken inside an adjacent laboratory, slightly tilted to drain off all excess water, and then weighed by suspension from an analytical balance. Unit-surface-area wet-weight increases per week thus served as the basis for the "growth modification factor" derived by these means for water fern. And, again, the temperature against which this factor was plotted was the mean air temperature of the current week and the immediately preceding week.

Throughout much of the time that water ferns were grown, sufficient tanks were available to have normally-sunlit and shaded treatments growing side-by-side. The shade screens utilized for this purpose filtered out fully 75 percent of the incoming solar radiation and, in summer, produced a greater reduction in light intensity than that normally experienced in going from summer to winter at our location under natural conditions. The reason for conducting this sub-experiment was to obtain data to differentiate between solar radiation and temperature effects, since these two parameters generally vary in phase with each other with the changing seasons.

Since each of our treatment chambers contained two water tanks, and since there were duplicate 340- and 640-ppm chambers, we were also able to periodically grow water hyacinths under the same experimental conditions, which we did from February of 1986 onward. Again, changes in unit-surface-area wet-weight provided the basis for our growth assessments; while the temperatures utilized were means of each week and the immediately preceding week.

C. Old Experiments

In addition to conducting new experimental work, we were able to utilize data we had collected in several other studies of the past few years. From a previous study (Idso *et al.*, 1985) of water hyacinths grown in the same CO_2 enrichment chambers and holding tanks, for instance, we were able to obtain eleven weekly fresh-weight biomass results for the summer of 1984. Also, in the three prior CO_2 enrichment studies of cotton (*Gossypium hirsutum* L. var. Deltapine-61) conducted by Kimball *et al.*, 1983, 1984, 1985, throughout the summer growing seasons of 1983, 1984 and 1985, weekly or bi-weekly destructive harvests of a number of plants had been made in each chamber; and the plants thereby obtained had been analyzed for total dry-weight biomass. Thus, from the data repositories of these experiments, we obtained twenty-two new dry-weight-based growth modification factors for another plant growing at the high end of the temperature range experienced at Phoenix.

D. Results and Discussion

Although data collection is continuing for all five species, with new information becoming available weekly, a sufficient number of measurements has already been obtained to demonstrate that there is indeed a strong interaction between air temperature and the effects of atmospheric CO_2 enrichment on plant growth and development.

The evidence for this claim is contained in Figure 44, where we have plotted the growth modification factors which result from a 300-ppm increase in atmospheric CO_2 concentration as a function of mean air temperature for all five species individually. As can be seen there, the results for all five plants clearly portray an upward trend in growth modification factor as mean air temperature increases. And, from the

normally-sunlit and 75-percent-reduced-sunlight results for water fern--which we obtained over the entire range of air temperatures encountered during our studies--it is clear that this trend is not in any way related to concurrent solar radiation variability, but is instead due solely to air temperature.

Since the results for all five species appear very similar, it is not unreasonable to believe that the phenomenon we have documented may be rather general throughout the plant kingdom. Thus, to obtain a reasonable estimate of what that general relationship may be like, we have combined all of our data to produce the conglomerate graph of Figure 45, where we have fit both linear and exponential functions to the data.

Assuming for the present that one of the relationships of Figure 45 is broadly representative of Earth's vegetation in general--which must obviously be confirmed by more studies of this type on more plant species--it is interesting to assess the implications for a mean surface air temperature increase of the magnitude predicted by the U.S. National Research Council (1979) to result from the "greenhouse effect" of a doubling of the Earth's atmospheric CO_2 concentration, i.e., a warming of 3°C. Using the linear relationship of the conglomerate graph of Fig. 2, we calculate that a 3°C increase in mean air temperature will raise the +300 ppm CO_2-induced growth modification factor from 1.30 to 1.56. And if we additionally accept the recent conclusion of Ramanathan _et al_. (1985) that "the radiative effects of increases in trace gases (other than CO_2) are as important as that of CO_2 increase in determining the climate change of the future or the past 100 years," the growth modification factor increases still further--as a result of another 3°C increase in air temperature--to 1.83. Similar calculations based on the exponential relationship of Figure 45 yield growth modification factors of 1.56 and 1.87 for these two situations. Thus, the net effect of the combined CO_2-trace gas greenhouse effect as currently perceived by most scientists working in that field may well be to almost triple the productivity enhancement expected to result from the direct fertilization effects of a 300 ppm increase in atmospheric CO_2 concentration under unchanging climatic conditions.

While the relative increases in growth due to doubled CO_2 at higher temperatures probably will be large, the absolute increases will be smaller if the new higher temperatures are above the optimum for plant growth. Indeed, the higher temperatures may cause a decrease in growth. Nevertheless, the higher CO_2 should cause the decrease to be less than it otherwise would have been.

At low temperatures, the effects of CO_2 are actually negative. As can be seen from both Figures 44 and 45, below a mean air temperature of about 18.5°C, atmospheric CO_2 enrichment tends to _reduce_ plant productivity. Thus, whereas plants like cotton which are adapted to warm climates may benefit immensely from atmospheric CO_2 enrichment--as cotton obviously does--plants adapted to cold climates may actually suffer from

atmospheric CO_2 enrichment. On the other hand, it is also possible that the greenhouse effect of higher atmospheric CO_2 concentrations may be strong enough to raise the surface air temperature by a more-than-compensatory amount, so that even in these colder areas atmospheric CO_2 enrichment may have a stimulatory effect on plant growth and development. Indeed, there is good reason to believe that this may in fact occur because the standard climate models of the CO_2 greenhouse effect (U.S. National Research Council, 1979) predict that the CO_2-induced warming of the Earth's high latitude regions will be several times greater than that experienced by the rest of the planet.

More work of this nature is thus urgently needed. Sufficient data must be obtained to produce relationships such as those of Figure 44 for more individual plant species, after which possible species differences can be more confidently discussed. Also, still colder and warmer temperature extremes should be investigated, in order to determine which of the two relationships of Figure 45 is the more realistic; for the two curves we have fit to the data will dramatically diverge from each other outside the range of temperatures within which we have so far worked.

Although future studies will undoubtedly refine the conclusions we have reached here, we are confident that our general observations will remain valid; for we have found them to be present in all five species tested to date (over a minimum of three growth cycles each), including two aquatic plants and three terrestrial ones.

SUMMARY AND CONCLUSIONS

The CO_2 concentration of the atmosphere is increasing and is expected to double sometime during the next century. To determine what effects this CO_2 increase is likely to have on the productivity, water relations, and physiological processes of field-grown cotton (as well as a few other plants), the USDA-ARS U. S. Water Conservation Laboratory and the Western Cotton Research Laboratory conducted CO_2 enrichment experiments on field-grown cotton and other plants during 1986. This report presents the results of those experiments, as well as further analyses of data collected in 1985.

There were 3 types of experiments. In the largest experiment, called the CO_2/WATER/NITROGEN experiment, the effects of the three-way interaction between increased CO_2 concentration, water stress, and low nitrogen fertility on the growth of cotton were investigated. Using open-top chambers, CO_2 concentrations of ambient (340 $\mu\ell/\ell$) and 640 $\mu\ell/\ell$ were maintained. There was a well-watered treatment and a water-stress treatment that received 2/3 as much water. Half the plots received 96 kg/ha of N as urea in the irrigation water while the others received no added fertilizer nitrogen. Significant findings from this experiment included the following:

1. For the N+ plots, CO_2-enrichment increased seed cotton (lint + seed) yields by 48% under well-watered conditions and by 70% under

water-stress. A larger response to CO_2 under water-stress is consistent with most prior data. For the N- plots, however, the tendency was reversed with a 70% increase from CO_2 enrichment under well-watered conditions, but a 51% increase under water-stress. Nevertheless, such responses to CO_2 under low-fertility are large and unexpected based on prior nutrient solution culture work.

2. The cycles of flowering, boll loading and cut-out which are typical of cotton growth were altered by the treatments and their interactions. Both the duration and amplitude of the flowering and boll-set cycles were altered by CO_2 enrichment and there were interactions with N- and water-stress. By mid-season, the treatments were out of phase with some treatments at maximum rate of flowering and others in cut-out. This behavior has serious implications for forecasts of crop behavior in future climates of increased CO_2. The absolute and relative productive response to the treatments will be a function of length of season and the phase of the fruiting cycle when the season terminates.
3. Aggregating all the cotton yield data from similar CO_2-enrichment experiments from 1983-1986, including water and nitrogen stress treatments, a near-doubling of CO_2 concentration from 350 to 650 $\mu\ell/\ell$ increased seed cotton yields an overall average 70%.
4. Net leaf photosynthesis was increased 51% at midseason by CO_2 enrichment when measured 2 days after irrigation, decreasing to 37% late in the season. Neither the irrigation nor the nitrogen treatments affected net photosynthesis.
5. Stomatal conductance was decreased about 11% at midseason by CO_2 enrichment when measured 2 days after irrigation, and was decreased 25% late in the season, determined by 2 independent techniques. The nitrogen treatment did not affect stomatal conductance. The water-stress treatment tended to decrease conductances, but the differences were not statiscally different (0.05). More striking than any treatment effects was a sharp decline in stomatal conductance late in the season, apparently associated with decreased temperature or possibly humidity.
6. Correlations of photosynthetic rate and stomatal conductance indicated there was factor coupling photosynthetic capacity with stomatal conductance that is effective only at enriched levels of CO_2.
7. Studies using microinjections of abscisic acid (ABA) into the veins of leaves showed that CO_2-enrichment greatly enhanced stomatal responsiveness to ABA, i.e., the ABA injections caused greater stomatal closure in the leaves of CO_2-enriched plants. Neither the water nor nitrogen stress treatments affected stomatal responsiveness to ABA.
8. CO_2-enrichment more than doubled the starch content of the cotton leaves. Nitrogen fertilizer had no significant effect nor did the irrigation treatment.
9. The well-watered irrigation treatment and the added-nitrogen treatment tended to decrease stomatal densities (no. of stomates/unit leaf area), consistent with the idea that leaves tend to have a set number of stomates and treatments that tend to

cause larger leaves result in lower stomatal densities. Contrary to this concept, however, CO_2 enrichment increased stomatal densities about 10%, and it also increased the ratio of lower to upper surface densities from 1.93 to 2.09.

10. A near-doubling of CO_2 concentration was again shown to increase foliage temperatures about 1.0°C. The nitrogen treatments had no significant effect, and of course, the water-stress treatment caused the leaves to be warmer.
11. Neither leaf water potential nor relative leaf water content was affected by the soil nitrogen treatments. As expected, the water stress treatment caused the leaves to be drier. Because CO_2 enrichment tended to partially close the stomates (see finding #5), an improvement in internal water relations was expected at high CO_2. Contrary to this hypothesis, CO_2 enrichment tended to make the leaves drier, so the higher yields (see finding #1) were obtained in spite of an apparent worsening of leaf water status.
12. Pan evaporation in the open-top chambers was similar to that outside early in the season, but by the end of the season inside pan evaporation was 5% greater than outside, unlike last year when it was 10% less. Soil nitrogen did not affect pan evaporation, but the water-stress treatment increased it 3%, a difference that was not statistically significant. CO_2 enrichment caused an unexpected but significant decrease of 6% in pan evaporation.
13. Rates of pink bollworm (Pectinophora gossypiella (Saunders)) development in cotton bolls manually infested with newly-hatched larvae were similar for cotton growing under ambient and CO_2-enriched treatments, indicating that this important cotton seed-feeding pest probably will not become any more or less of a problem in the future high CO_2 world.
14. Soil CO_2 concentrations were again found to be much lower in the soil within the open-top chambers than outside. Air pressure measurements showed that there were regions of consistently higher air pressure beneath the perforated 20-cm-dia. air/CO_2 distribution tubes and also just inside the chamber walls. Therefore, it seems likely that pressure gradients from the blower/distribution system flushed CO_2 out of the soil atmosphere. No differences were found between chambers so it is unlikely these low soil CO_2 concentrations affected the cotton growth results.

The second experiment, called the FIZZ/FACE experiment, the effects of CO_2 on cotton growing in a open field (no chambers) was observed. The CO_2 was applied using two methods - (1) irrigating with carbonated water (FIZZ) and (2) releasing CO_2 at the soil surface, a free-air CO_2 enrichment (FACE) experiment. The entire field was irrigated 6 days per week with the same ample amount of water from drip irrigation tubing, the water for the FIZZ treatment being supersaturated with CO_2 from a commercial carbonator first. The CO_2 to the FACE plots was distributed through a second set of drip irrigation tubing at a release rate of 10 mg m^{-2} s^{-1} from 06:00 to 17:00 daily. Both treatments started near the end of June when the crop canopy was near full development and continued

until harvest near the beginning of October. Control plots received normal irrigation and no free-air CO_2. There were 4 replications. Significant findings from the FIZZ/FACE experiment included the following:

1. The pH of the irrigation water was lowered from 7.5 to 5.1 in the FIZZ treatment. Soil pH was lowered about 1.5 units. Soil CO_2 concentrations at shallow depths increased rapidly during a morning irrigation of a FIZZ plot and then decreased to close to predawn levels by dusk. Concentrations at 40-60 cm were fairly constant but higher than the control plots.
2. Average daytime atmospheric CO_2 concentrations at 75% of plant height were 360, 364, and 522 $\mu\ell/\ell$ for the control, FIZZ, and FACE plots, respectively. The hourly average FACE concentrations at 75% of plant height ranged from 700 $\mu\ell/\ell$ at 7 am when the wind was generally calm to a minimum of about 440 $\mu\ell/\ell$ in the midafternoon when turbulence levels were higher. The corresponding concentrations lower in the crop canopy at 25% of plant height were 1400 and 600 $\mu\ell/\ell$, respectively.
3. Total seed cotton yield was increased 11 and 22% by the FIZZ and FACE treatments, respectively (when the yield of 1 abnormally productive control plot was ignored).
4. Net leaf photosynthesis and stomatal resistance were significantly increased about 9% by the FACE treatment, but there was no detectable effect of the FIZZ treatment. Neither treatment affected the leaf water potential or the relative leaf water content of this well-watered cotton.
5. Leaf starch content was increased about 40% by the FACE treatment, but the FIZZ treatment had no significant effect.

A third set of experiments investigated the interaction of temperature on the CO_2 growth response of plants. Carrot, radish, water hyacinth, and azolla (water fern) were grown throughout the year in open-top CO_2 enrichment chambers exposed to an average daily temperature that ranged from 12 to 34 C at Phoenix, Arizona, and weekly growth measurements were made. Similar weekly growth data from cotton growing from May through July in prior experiments were utilized. Significant findings from these temperature interaction experiments include the following:

1. The growth stimulation due to a near-doubling of CO_2 concentration was strongly temperature dependent. The "growth modification factor" varied from about -60% at 12°C to 0% at 19°C to +130% at 34°C.
2. Utilizing prior comprehensive analyses of CO_2 enrichment experiments reported in the literature that indicate a near-doubling of atmospheric CO_2 concentration will increase plant yields about 30%, and also utilizing the climate modelers' prediction that a doubling of CO_2 concentration will increase mean surface air temperature about 3 C, these results suggest that plant growth may be stimulated by about 56% (rather than 30%).
3. Plants grown at mean air temperatures below about 19 C probably will suffer from CO_2 enrichment.

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Table 1. Carbon isotope ratios for cotton lint samples harvested from the 1985 open-topped CO_2-enrichment enclosures.

Sample	^{14}C / ^{12}C	^{13}C / ^{12}C	CHAMBER CO_2 CONTENT		
			Calculated		
			From ^{14}C	From ^{13}C	Measured*
	(% Modern)	(ppm)	$\mu\ell\ \ell^{-1}$		
CO_2 Gas	0.0	35.4			
CO_2 Atmosphere	100.0	7.0			
650 W - I	55.7	45.5	721	916	639
650 W - II	59.7	43.2	673	753	640
650 D - I	76.6	39.1	548	567	655
AMB W - I	118.3	27.8			347
AMB D - I	123.3	27.5			353

* Seasonal average daytime CO_2 concentrations from Kimball et al., 1985.

Table 2. Predawn mean moduli of elasticity for the 1985 experiment (Kimball et al., 1985). The individual treatment means are averages over 2 reps and 3 biweek intervals during the season, thereby producing 6 observations per mean. No CO_2 or irrigation main treatment differences were significant at the 0.05 level based on an analysis of variance F test considering biweeks as a main plot effect or as a sub-sub-sample. The apparent interaction between CO_2 and irrigation was significant when biweeks were considered as a main treatment effect.

	CO_2 TREATMENT				Averaged over CO_2
	Open	Chamber CO_2 Conc. ($\mu\ell\ \ell^{-1}$)			
IRRIGATION	Field	Ambient	500	650	
	MPa				
Wet	6.15	6.29	4.87	1.61	4.73
Dry	4.80	5.07	6.96	6.85	5.92
Averaged Over Irrig.	5.48	5.68	5.91	4.23	5.32

Table 3. Afternoon mean moduli of elasticity for the 1985 experiment (Kimball et al., 1985). The individual treatment means are averages over 2 reps and 2 biweek sampling intervals during the season, thereby producing 4 observations per mean. No CO_2 or irrigation treatment differences were significant at the 0.05 level based on an analysis of variance F test considering biweeks as a main effect or as a sub-sub-sample.

	CO_2 TREATMENT				Averaged over CO_2
	Open	Chamber CO_2 Conc. ($\mu\ell\ \ell^{-1}$)			
IRRIGATION	Field	Ambient	500	650	
	MPa				
Wet	6.76	7.83	4.07	7.02	6.42
Dry	4.17	4.94	4.83	5.37	4.83
Averaged Over Irrig.	5.47	6.39	4.45	6.20	5.63

Table 4. Predawn mean non-osmotic relative leaf water contents for the 1985 experiment (Kimball et al., 1985). The individual treatment means are averages over 2 reps and 3 biweek sampling intervals during the season, thereby producing 6 observations per mean. No CO_2 or irrigation treatment differences were significant at the 0.05 level based on an analysis of variance F test considering biweeks as a main effect or as a sub-sub-sample.

	CO_2 TREATMENT				Averaged over CO_2
	Open	Chamber CO_2 Conc. ($\mu\ell\ \ell^{-1}$)			
IRRIGATION	Field	Ambient	500	650	
	%				
Wet	11.0	23.7	20.8	14.1	17.4
Dry	30.7	23.6	21.9	24.7	25.2
Averaged Over Irrig.	20.9	23.7	21.3	19.4	21.3

Table 5. Afternoon mean non-osmotic relative leaf water contents for the 1985 experiment (Kimball et al., 1985). The individual treatment means are averages over 2 reps and 2 biweek sampling intervals during the season, thereby producing 4 observations per mean. CO_2 differences only were significant at the 0.05 level based on an analysis of variance F test considering biweeks as a main effect but no differences were significant treating biweeks as a sub-sub-sample.

	CO_2 TREATMENT				Averaged over CO_2
	Open	Chamber CO_2 Conc. ($\mu\ell\ \ell^{-1}$)			
IRRIGATION	Field	Ambient	500	650	
	kPa				
Wet	38.8	13.5	7.2	27.9	21.8
Dry	12.0	15.4	7.7	18.7	13.5
Averaged Over Irrig.	25.4	14.5	7.4	23.2	17.7

Table 6. Insecticide treatments applied during CO_2-cotton 86 experiment. Rates were those recommended by label, except Pydrin at 0.11 kg/ha.

Date	Insecticide	Area Applied Chambers	Open field
24 April	Orthene		X
8 May	Orthene	X	
23 May	Orthene	X	
23 May	Malathion		X
28 May	Malathion	X	X
28 June	Orthene	X	X
5 July	Orthene	X	X
8 July	Malathion	X	X
14 July	Malathion	X	X
19 July	Malathion	X	X
24 July	Malathion	X	X
29 July	Malathion	X	X
2 August	Malathion	X	X
7 August	Malathion	X	X
12 August	Dimilin	X	X
12 August	Kelthane	X	X
23 August	Pydrin	X	X
30 August	Pydrin	X	X
4 September	Malathion	X	X
9 September	Malathion	X	X
13 September	Malathion	X	X
20 September	Pydrin	X	X

Table 7. Irrigation and rain amounts for the CO_2-cotton 1986 experiment.

DATE	DAY of YEAR	IRRIG. (I) or RAIN (R)	WET PLOTS N+	WET PLOTS N-	DRY PLOTS N+	DRY PLOTS N-
			mm			
23 Apr	113	I	23.0	24.1	24.7	23.0
13 May	133	I	14.1	12.1	6.7	10.5
20 May	140	I	17.5	17.9	13.9	11.5
22 May	142	I	24.6	22.0	14.7	12.6
27 May	147	I	3.4	6.1	5.5	4.5
1 Jun	152	R	0.5	0.5	0.5	0.5
3 Jun	154	I	19.8	20.3	14.0	13.6
10 Jun	161	I	61.6	52.2	40.5	35.1
17 Jun	168	I	52.6	65.9	30.2	46.6
24 Jun	175	I	96.4	79.0	78.1	51.7
1 Jul	182	R	10.9	10.9	10.9	10.9
1 Jul	182	I	79.0	99.8	38.1	63.7
2 Jul	183	R	14.0	14.0	14.0	14.0
4 Jul	185	R	1.3	1.3	1.3	1.3
8 Jul	189	I	73.5	59.1	44.0	30.2
15 Jul	196	I	69.4	80.6	47.4	50.6
21 Jul	202	R	15.2	15.2	15.2	15.2
22 Jul	203	I	70.2	69.2	43.6	48.7
29 Jul	210	I	66.2	63.5	38.3	33.6
5 Aug	217	I	81.1	82.4	56.0	58.7
7 Aug	219	R	2.8	2.8	2.8	2.8
9 Aug	221	R	1.1	1.1	1.1	1.1
12 Aug	224	I	80.2	79.0	50.2	47.6
19 Aug	231	I	59.2	66.0	42.8	44.1
25 Aug	237	R	0.5	0.5	0.5	0.5
26 Aug	238	R	5.3	5.3	5.3	5.3
26 Aug	238	I	150.4	162.1	125.0	132.7
27 Aug	239	R	23.1	23.1	23.1	23.1
28 Aug	240	R	0.8	0.8	0.8	0.8
29 Aug	241	R	2.0	2.0	2.0	2.0
9 Sep	252	I	69.7	50.7	4.2	0.0
16 Sep	259	I	59.6	51.8	38.9	37.4
23 Sep	266	R	9.7	9.7	9.7	9.7
23 Sep	266	I	58.4	62.0	41.2	39.6
25 Sep	268	R	0.5	0.5	0.5	0.5
30 Sep	273	I	33.4	39.4	15.6	20.5
		Totals	1345.7	1352.9	901.3	904.2

Table 8. Total water use during the CO_2-cotton 1986 experiment as determined by the total amount of water applied through the drip irrigation system and adjusted for changes in soil moisture storage measured with neutron apparatus. A pre-irrigation of about 150 mm was applied by flooding in February, but this is not included in the water use values.

ITEM	TREATMENT							
	No Added N				Added N			
	Ambient		650		Ambient		650	
	Rep I	Rep II	Rep I	Rep II	Rep I	Rep II	Rep I	Rep II
WET PLOTS:								
10 Apr. soil water content	386	241	445	208	390	350	431	195
6 Oct. soil water content	433	236	384	207	452	347	434	189
Soil water content change	-47	+5	+61	+1	-62	+3	-3	+6
Irrigation & rain (23 Apr. - 30 Sep.)	1353	1353	1353	1353	1346	1346	1346	1346
Water use	1306	1358	1414	1354	1284	1349	1343	1352
average water use	1332		1384		1316		1347	
relative water use	1.000		1.039		1.000		1.024	
DRY PLOTS:								
10 Apr. soil water content	337	258	378	259	325	280	370	259
6 Oct. soil water content	244	214	316	198	233	216	267	181
Soil water content change	+93	+44	+62	+61	+92	+64	+103	+78
Irrigation & rain (23 Apr. - 30 Sep.)	904	904	904	904	901	901	901	901
Water use	997	948	966	965	993	965	1004	979
average water use	972		965		979		991	
relative water use	1.000		0.993		1.000		1.012	

Table 9. Total amounts of nitrogen applied to the plots in the CO_2-cotton 1986 experiment as urea-N injected into the irrigation water, as NO_3^--N naturally occurring in the irrigation water, and as the change in NO_3^--N in the soil during the growing season.

	TREATMENT	
	NONE ADDED (N^-)	ADDED (N^+)
Urea - N	0	96
Irrigation NO_3^- - N	5	5
Change in Soil NO_3^- - N (150 mm depth)	37	37
TOTAL	42	138

Table 10. Daytime, nighttime, and whole day mean chamber CO_2 concentrations and the corresponding standard deviations of the individual observations for the entire season of the CO_2-cotton 86 experiment.

		TREATMENT			
		Ambient		650	
REP	IRRIGATION	N^-	N^+	N^-	N^+
		$\mu\ell\ \ell^{-1}$			
Daytime:					
I	WET	355±38	357±40	641±72	645±78
II	WET	351±38	351±38	646±68	640±73
I	DRY	358±39	352±38	642±73	643±68
II	DRY	360±39	362±41	645±77	641±65
	Average Over Reps, Irrigation, and Nitrogen:	356±39		643±72	
Nighttime:					
I	WET	389±47	392±50	654±60	661±64
II	WET	380±48	385±49	655±64	651±59
I	DRY	390±50	381±47	655±64	658±59
II	DRY	392±51	400±56	661±76	657±59
	Average Over Reps, Irrigation, and Nitrogen:	389±50		657±64	
Whole (24 hr) Day:					
I	WET	371±46	373±48	647±67	652±72
II	WET	365±45	367±47	650±67	645±67
I	DRY	373±47	365±45	648±69	650±65
II	DRY	375±48	380±52	652±77	648±63
	Average Over Reps, Irrigation, and Nitrogen:	371±48		649±69	

Table 11. Analysis of variance for the experimental design of Figure 1 with irrigation as the main plot treatment, CO_2 and nitrogen as sub-plot treatments, 4 biweeks of repeated sampling through the growing season as a sub-sub-sampling, and finally 2 leaves per chamber were measured for a sub-sub-sub-sampling.

Source of Variation	Degrees of Freedom
R, Replicates	1
I, Irrigation	1
error a	1
C, CO_2	1
I x C	1
N, Nitrogen	1
I x N	1
C x N	1
I x C x N	1
error b	6
B, biweeks	3
I x B	3
C x B	3
I x C x B	3
N x B	3
I x N x B	3
C x N x B	3
I x C x N x B	3
error c	24
L, leaves	1
I x L	1
C x L	1
I x C x L	1
N x L	1
I x N x L	1
C x N x L	1
I x C x N x L	1
B x L	3
I x B x L	3
C x B x L	3
I x C x B x L	3
N x B x L	3
I x N x B x L	3
C x N x B x L	3
I x C x N x B x L	3
error d	32

Table 12. Analysis of variance for the experimental design of Figure 1 with irrigation and 4 biweeks of repeated sampling through the growing season as main treatment effects, CO_2 and nitrogen as sub-plot treatments, and finally 2 leaves per chamber as sub-sub-sampling.

Source of Variation	Degrees of Freedom
R, Replicates	1
B, Biweeks	3
I, Irrigation	1
B x I	3
error a	7
C, CO_2	1
B x C	3
I x C	1
B x I x C	3
N, Nitrogen	1
B x N	3
I x N	1
B x I x N	3
C x N	1
B x C x N	3
I x C x N	1
B x I x C x N	3
error b	24
L, leaves	1
B x L	3
I x L	1
B x I x L	3
C x L	1
B x C x L	3
I x C x L	1
B x I x C x L	3
N x L	1
B x N x L	3
I x N x L	1
B x I x N x L	3
C x N x L	1
B x C x N x L	3
I x C x N x L	1
B x I x C x N x L	3
error c	32

Table 13. Final harvest data from open-topped enclosures with CO_2-enrichment (C+) to 650 ppm or ambient (C-) CO_2 and 96 kg/ha nitrogen added (N+) or no additional nitrogen during the year (N-).

CARBON DIOXIDE	650 ppm (C+)								AMBIENT (C-)							
IRRIGATION	WET				DRY				WET				DRY			
FERTILITY	N+		N-		N+		N-		N+		N-		N+		N-	
REPLICATION	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II
Plant/m^2	12.0	11.3	11.0	11.0	11.7	10.3	10.7	11.0	11.0	11.0	9.0	7.7	11.7	11.7	11.3	12.0
Plant Ht. (cm)	81	77	79	75	66	79	68	66	68	68	67	71	60	66	59	57
Bolls/m^2	756	750	742	681	698	721	702	660	499	499	471	404	406	410	418	467
Top Dry Wt. (g/m^2)	1701	1657	1698	1516	1355	1363	1284	1283	1183	1098	1050	884	780	755	816	805
Root Dry Wt. (g/m^2)	96	119	84	87	100	83	82	177	66	87	52	55	43	60	53	70
Total D.W. (g/m^2)	1797	1776	1782	1603	1455	1446	1366	1460	1249	1185	1102	939	823	815	869	875
Ave. D.W. (g/m^2)	1787		1741		1451		1413		1217		1021		819		872	
Rel. CO_2 Effect	1.47		1.70		1.77		1.62		1.00		1.00		1.00		1.00	
Lint Wt. (g/m^2)[1]	254	255	250	202	208	277	168	190	165	168	157	150	108	90	111	112
Seed Wt. (g/m^2)	391	401	413	339	312	285	253	275	273	271	254	229	280	141	188	170
% Lint	39	39	37	37	40	38	40	41	38	38	38	40	38	39	37	40
Seed Cotton [2](g/m^2)	961	991	991	910	785	741	724	711	636	680	592	523	439	460	464	489
Average (g/m^2)	976		950		763		717		658		557		449		476	
Rel. CO_2 Effect	1.48		1.70		1.70		1.51		1.00		1.00		1.00		1.00	
Seed Index (g/100)	10.8	10.5	11.5	10.3	10.7	10.3	10.7	10.7	10.4	11.0	10.0	11.0	10.5	10.0	10.6	10.0
Harvest Index[3] (%)	56	60	58	58	58	54	56	55	54	62	56	59	56	61	57	61

1 Does not include weight of green, unopened bolls at time of harvest.
2 Includes estimated seed cotton weight for green bolls at time of harvest.
3 Seed cotton weight/top weight.

Table 14. Percentage increase in seed cotton yield due to a near-doubling of CO_2 under high and low water and nitrogen (averaged over reps).

NITROGEN	Year		IRRIGATION Well-watered	Water-stressed
			------- % -------	
Added (high)	83		63	-
	84		94	77
	85		52	104
	86		48	70
		Ave.	64	84
None added (low)	86		70	51
Average high & low N			65	76
Overall average			70	

Table 15. Leaf area (cm^2) per active boll (40 days or less) in the open-topped chambers. Data are averages of the N+ and N- treatments and the two replications of the 650 ppm CO_2 (C+) and ambient (C-) treatments of the wet (W) and dry (D) plots.

TREATMENT Julian date	WC+	WC-	DC+	DC-
161	860	687	707	323
168	260	234	232	308
175	181	250	167	360
182	179	256	420	213
189	205	296	279	284
196	214	446	573	368
203	628	505	346	402
210	270	420	181	278
217	3450	525	212	193
231	284	685	280	455
246	276	323	280	966

Table 16. Mineral content of cotton leaves from the CO_2/WATER/NITROGEN and the FIZZ/FACE experiments (averaged over reps) sampled on day 215 (3 August 1986), as determined by a commercial laboratory.

Element	N (%)	P (%)	K (%)	CA (%)	Mg (%)	S (%)	Na (%)	Fe (ppm)	Zn (ppm)	Mn (ppm)	Cu (ppm)	B (ppm)
Treatment												
WC^+N^+	2.8*	.30	3.2	4.1	.81	1.6	.25	111	28*	110	11	105
WC^+N^-	1.8*	.24*	3.0	4.3	.90	2.0	.23	157	22*	95	10	146
WC^-N^+	3.3	.25*	3.2	4.6	.89	1.8	.27	145	31	127	11	110
WC^-N^-	2.9*	.30	3.2	4.3	.90	2.0	.32	147	29*	110	13	125
DC^+N^+	2.7*	.28*	2.8	4.0	.86	1.5	.14	199	34	112	13	142
DC^+N^-	2.8*	.30	2.9	3.7	.84	1.7	.15	177	36	103	11	130
DC^-N^+	3.1	.32	2.8	4.8	.90	1.7	.17	210	37	126	18	192
DC^-N^-	3.1	.35	3.0	4.0	.88	1.9	.17	249	37	110	13	210
FACE	2.5*	.30	3.0	4.8	.81	2.1	.22	205	20*	94	9	135
FIZZ	2.5*	.35	3.0	4.9	.87	2.2	.21	204	21*	81	11	155
CONT	2.4*	.26*	3.0	5.1	.84	2.1	.22	238	21*	86	11	155

* Considered to be a deficient concentration of listed element.

Table 17. Mean net leaf photosynthesis for the main irrigation, CO_2, and nitrogen fertilizer effects for the 1986 CO_2-cotton experiment. The dividing time between mid and late season was mid-September. The means are averages over 2 reps, days, 3 leaves, and the other treatments, thus making the number of observations per mean equal to 24 times the number of sampling days. Means not followed by the same letter are significantly different at the 0.05 probability level from our analysis of variance F test considering the sampling days to be repeated measure sub-samples (Table 11). The numbers in parentheses are the percentage change due to CO_2 enrichment.

Days Since Irrig.	Portion of Season	No. Obs.	TREATMENT					
			Irrigation		CO_2		Nitrogen	
			Dry	Wet	Amb.	650	N^-	N^+
			μ mol m^{-2} s^{-1}					
2	mid	240	37.1a	35.0a	28.7a	43.4b (51%)	36.3a	35.7a
2	late	72	26.7a	25.4a	22.0a	30.1b (37%)	25.9a	26.3a
6	whole	144	25.4a	27.3a	22.2a	30.4b (37%)	26.4a	26.2a

Table 18. Mean stomatal conductances for the main irrigation, CO_2, and nitrogen fertilizer effects for the 1986 CO_2-cotton experiment. The dividing time between mid and late season was mid-September. The means are averages over 2 reps, days, 3 leaves, and the other treatments, thus making the number of observations per mean equal to 24 times the number of sampling days. Means not followed by the same letter are significantly different at the 0.05 probability level from our analysis of variance F test considering the sampling days to be repeated measure sub-samples (Table 11). The numbers in parentheses are the percentage change due to CO_2 enrichment.

Days Since Irrig.	Portion of Season	No. Obs.	TREATMENT: Irrigation		CO_2		Nitrogen	
			Dry	Wet	Amb.	650	N^-	N^+
			cm/s					
2	mid	240	2.55a	2.76a	2.82a	2.50b (-11)	2.69a	2.63a
2	late	72	0.85a	1.04a	1.08a	0.81b (-25)	0.98a	0.91a
6	whole	144	1.11a	1.99a	1.75a	1.36b (-22)	1.58a	1.53a

Table 19. Parameters of photosynthetic gas exchange during midseason (Day of year 177-219). Symbols and abbreviations: g_s, stomatal conductance to water vapor; CE, carboxylation efficiency, or slope of the $A(c_i)$ curve at limiting c_i; A, photosynthesis at chamber atmospheric CO_2 level; c_i, intercellular CO_2 concentration at chamber atmospheric CO_2 level; Γ, CO_2 compensation concentration; L, stomatal limitation to photosynthesis. Number of days of observation are shown after treatments. Numbers in parentheses are percentage change from ambient.

Treatment	No. Days	g_s	CE	A	c_i	Γ	L
		mol m^{-2} s^{-1}	mol m^{-2} s^{-1}	μmol m^{-2} s^{-1}	μℓ $ℓ^{-1}$	μℓ $ℓ^{-1}$	%
Ambient CO_2:							
dry N^-	4	1.09	0.15	26.0	304	110	17
wet N^-	8	1.20	0.15	26.8	308	98	14
dry N^+	5	1.14	0.15	26.9	305	102	15
wet N^+	7	1.09	0.15	26.0	305	102	16
Enriched CO_2:							
dry N^-	4	1.04	0.15	43.9 (69)	570	108	9
wet N^-	8	0.98	0.14	45.6 (70)	567	100	9
dry N^+	4	0.98	0.13	46.7 (74)	563	111	13
wet N^+	8	1.01	0.13	44.9 (73)	572	95	8

Table 20. Parameters of photosynthetic gas exchange during the late season (day of year 262-274). Symbols and abbreviations as in Table 19.

Treatment	No. Days	g_s	CE	A	c_i	Γ	L
		mol m^{-2} s^{-1}	mol m^{-2} s^{-1}	μmol m^{-2} s^{-1}	μℓ $ℓ^{-1}$	μℓ $ℓ^{-1}$	%
Ambient CO_2:							
dry N^-	3	0.38	0.13	24.0	247	45	28
wet N^-	3	0.39	0.11	20.5	265	44	22
dry N^+	3	0.43	0.12	24.6	256	46	25
wet N^+	3	0.39	0.13	21.4	259	42	25
Enriched CO_2:							
dry N^-	3	0.29	0.11	36.7 (53)	445	59	11
wet N^-	3	0.33	0.10	33.3 (62)	486	51	14
dry N^+	4	0.31	0.09	32.4 (32)	481	53	20
wet N^+	3	0.28	0.10	28.6 (34)	482	55	6

Table 21. R^2 values for linear correlations between residuals of stomatal conductance and photosynthetic capacity. Residuals are calculated as the percentage deviation from the estimated value of stomatal conductance (mean of the population) or photosynthesis (determined from leaf C_i and population $A(C_i)$ curve).

Treatment	n	R^2	Significance Level
Ambient CO_2:			
dry N^-	28	0.01	NS
wet N^-	31	0.05	NS
dry N^+	27	0.04	NS
wet N^+	32	0.13	0.05
Enriched CO_2:			
dry N^-	32	0.50	0.01
wet N^-	29	0.14	0.05
dry N^+	26	0.30	0.01
wet N^+	27	0.17	0.05

Table 22. Effects of ABA injected into a leaf vein on stomatal conductance of leaves in the CO_2-cotton 1986 experiment. Data are the ratios of conductance 10 min after injection (g_s10) to conductance at the time of injection (g_s0). Results from all treatments are combined within CO_2 levels.

Date	Day of Year	Day After Irrig.	g_s10/g_s0	
			Ambient	650
6 Aug	218	1	0.74	0.19
7 Aug	219	2	0.55	0.24
11 Aug	223	6	0.34	0.10
25 Aug	237	6	0.30	0.15
15 Sep	258	6	0.30	0.21
29 Sep	272	6	0.67	0.68

Table 23. Mean starch content of cotton leaves in the 1986 CO_2/WATER/NITROGEN experiment that were sampled at sunrise and sunset 2 and 6 days following irrigation. Also, the mean changes in starch content from sunrise to sunset 2 and 6 days after irrigation and the mean changes from 2 to 6 days after irrigation at sunrise and at sunset. The means are averages over 2 replicates, 7 biweekly sampling periods, and the other treatments, thus making the number of observations per mean equal to 56. Means not followed by the same letter within a pair are significantly different (0.05) considering the biweekly sampling intervals to be repeated measure subsamples (Table 11). No interactions were significant. The numbers in parentheses are the ratios of the CO_2 enriched to the ambient starch levels.

DAYS SINCE IRRIG.	SAMPLING TIME	TREATMENT: IRRIGATION DRY	WET	CO_2 AMB.	650	NITROGEN N-	N+
		$g\ m^{-2}$					
Absolute starch contents:							
2	sunrise	10.1a	10.6a	5.6a	15.1b(2.70)	9.8a	10.9a
2	sunset	17.5a	19.3a	12.1a	24.7b(2.04)	18.0a	18.9a
6	sunrise	7.9a	8.7a	3.3a	13.3b(4.03)	8.1a	8.4a
6	sunset	11.7a	14.4a	7.8a	18.3b(2.35)	13.1a	13.0a
Change in starch content from sunrise to sunset:							
2	--	7.4a	8.7a	6.5a	9.6b(1.48)	8.2a	7.9a
6	--	3.9a	5.7a	4.6a	5.0b(1.09)	5.0a	4.6a
Change in starch content from 2 days to 6 days following irrigation:							
--	sunrise	2.3a	2.0a	2.3a	1.9a(0.83)	1.7a	2.5a
--	sunset	5.8a	5.0b	4.3a	6.5a(1.51)	4.9a	5.9a

Table 24. Mean stomatal densities of cotton during October for the CO_2-cotton experiment. Means within a treatment pair not followed by the same letter are significantly different at the 0.05 level by ANOVA.

	TREATMENT					
	Irrigation		CO_2		Nitrogen	
Leaf Surface	Dry	Wet	Amb.	650	N^-	N^+
	stomates mm^{-2}					
Adaxial (upper)	173a	151b	157a	167b (+6%)	167a	157a
Abaxial (lower)	341a	307a	302a	345b (+14%)	335a	313a
Ratio (Abaxial/Adaxial)	1.99a	2.03a	1.93a	2.09b	2.03a	1.99a

Table 25. Mean leaf water potentials (LWP) for the main irrigation, CO_2 and nitrogen fertilizer effects for the 1986 CO_2-cotton experiment. The means are averages over 2 reps, 2 leaves per rep, biweeks, and the other treatments, thus making the number of observations per mean equal to 16 times the number of biweekly sampling periods. Means not followed by the same capital letter are significantly different at the 0.05 probability level from an analysis of variance F test considering the biweekly sampling intervals to be an independent main effect. Means not followed by the same small letter are significantly different considering the biweekly intervals to be repeated measure subsamples.

			TREATMENT					
			IRRIGATION		CO_2		NITROGEN	
DAYS SINCE IRRIG.	SAMPLING TIME	NO. OBS.	DRY	WET	AMB.	650	N^-	N^+
			MPa					
2	Predawn	96	-1.25A a	-1.10A a	-1.15A a	-1.20B b	-1.18A a	-1.16A a
2	Afternoon	96	-1.87A a	-1.65A b	-1.75A a	-1.77A a	-1.77A a	-1.75A a
6	Predawn	64	-1.55A a	-1.29A a	-13.8A a	-1.47B b	-1.41A a	-1.43A a
6	Afternoon	64	-2.38A a[z]	-1.94B a[z]	-2.19A[y] a	-2.13A[y] a	-2.14A a	-2.18A a

[y] The CO_2 x biweek interaction was significant.
[z] The irrigation x biweek interaction was significant.

Table 26. Mean relative leaf water contents (RLWC) for the main irrigation, CO_2, and nitrogen fertilizer effects for the 1986 CO_2-cotton experiment. The means are averages over 2 reps, biweeks and the other treatments, thus making the number of observations per mean equal to 8 times the number of biweek sampling periods. Means not followed by the same capital letter are significantly different at the 0.05 probability level from an analysis of variance F test considering the biweekly sampling intervals to be an independent main effect. Means not followed by the same small letter are significantly different considering the biweekly intervals to be repeated measure subsamples.

			TREATMENT					
			IRRIGATION		CO_2		NITROGEN	
DAYS SINCE IRRIG.	SAMPLING TIME	NO. OBS.	DRY	WET	AMB.	650	N^-	N^+
			%					
2	Predawn	32	83.1A a	88.6A b	85.7A a	85.9A a	84.5A a	87.2A a
2	Afternoon	40	72.5A a	77.8B b	74.6A a	75.6A a	73.7A a	76.5A a
6	Predawn	32	82.3A a	87.2B a	86.7A a	82.9A a	84.8A a	84.7A a
6	Afternoon	24	75.2A a	77.9A a	78.6A a	74.5B a	76.9A a	76.2A a

Table 27. Mean dry matter contents (DMC) for the main irrigation, CO_2, and nitrogen fertilizer effects for the 1986 CO_2-cotton experiment. The means are averages over 2 reps, biweeks, and the other treatments, thus making the number of observations per mean equal to 8 times the number of biweek sampling periods. Means not followed by the same capital letter are significantly different at the 0.05 probability level from an analysis of variance F test considering the biweekly intervals to be repeated measure subsamples.

			TREATMENT					
			IRRIGATION		CO_2		NITROGEN	
DAYS SINCE IRRIG.	SAMPLING TIME	NO. OBS.	DRY	WET	AMB.	650	N^-	N^+
			%					
2	Predawn	40	24.2A a	22.3A a	21.5A a	25.0B b	23.8A a	22.7A a
2	Afternoon	40	27.8A a	25.9A a	25.4A a	28.2B b	27.1A a	26.6A a
6	Predawn	24	21.4A a	20.5A a	19.2A a	22.6B b	22.0A a	19.8A a
6	Afternoon	24	25.6A a	24.8A a	22.9A a	27.5B b	25.6A a	24.8A a

Table 28. Cumulative pan evaporation during the CO_2-cotton 86 experiment.

Class A: 1749 mm
Small Standard: 2311 mm

Chambers:

	TREATMENT							
	Wet				Dry			
Individual chambers:	Amb.		650		Amb		650	
Rep	N^-	N^+	N^-	N^+	N^-	N^+	N^-	N^+
	mm							
I	1512	1524	1462	1420	1594	1591	1500	1515
II	1553	1525	1515	1442	1611	1580	1436	1474
Mean	1533	1525	1489	1431	1603	1585	1468	1494

Treatment Means:

TREATMENT					
Irrigation		CO_2		Nitrogen	
Wet	Dry	Amb.	650	N^-	N^+
1494a	1537a	1561a	1471b	1523a	1509a

Overall Chamber Mean: 1516 mm

Open Field (Rep 1):

TREATMENT			
Control	FIZZ	FACE	Mean
mm			
1482	1431	1419	1444

Table 29. Mean pupal weights[1] of *P. gossypiella* reared on cotton grown in enriched and ambient carbon dioxide atmospheres.

Site	Trial	Carbon dioxide in atmosphere					
		Enriched[2]			Ambient[3]		
		n	Wt (mg) ±	SEM	n	Wt (mg) ±	SEM
Chambers	1	57	27.11[a]	0.61	46	27.21[a]	0.66
Chambers	2	24	27.57[a]	1.46	22	26.18[a]	0.90
Means		81	27.25[a]	0.60	68	26.87[a]	0.53
FACE[4]		44	25.98[a]	0.68	21	25.89[a]	0.97
Means		125	26.80[a]	0.46	89	26.64[a]	0.47

[1] 0 - 24 h after pupation, males and females pooled.

[2] 650 and 522 μℓ/liter for the chambers and FACE plots, respectively.

[3] 360 μℓ/liter

[4] Field plot with free-air CO_2 enrichment.

[a] No significant difference ($P > 0.05$) between any of the treatments or replicates (2-way and 1-way ANOVA for all meaningful combinations).

Table 30. Length of development[1] of *P. gossypiella* reared on cotton grown in enriched and ambient carbon dioxide atmospheres.

Site	Trial	Carbon dioxide in atmosphere								
		Enriched[2]			Ambient[3]			Means		
		n	days	± SEM	n	days	± SEM	n	days	± SEM
Chambers	1	57	21.2^a	0.5	46	23.6^a	1.0			
Chambers	2	25	21.4^a	0.6	22	21.3^a	1.0			
Means		82	21.2^a	0.4	68	22.9^a	0.8	150	22.0^a	0.4
FACE[4]		46	27.3^b	1.7	21	25.4^b	1.2	67	26.7^b	1.3
Means		128	23.4	0.7	89	23.5	0.7			

1 Neonate larval to pupal stage, males and females pooled.

2 650 and 522 μℓ/liter for the chambers and FACE plots, respectively.

3 360 μℓ/liter

4 Field plot with free-air CO_2 enrichment.

a,b Means in each column or row followed by the same letter are not significantly different ($P > 0.05$). Means followed by a different letter are significantly different ($P < 0.0002$).

Table 31. Mean percent seed damage to cotton bolls by larvae[1] of *P. gossypiella* reared on cotton grown in enriched and ambient carbon dioxide atmospheres.

		Carbon dioxide in atmosphere								
Site	Trial	Enriched[2]			Ambient[3]			Means		
		n	days	± SEM	n	days	± SEM	n	days	± SEM
Chambers	1	39	30.9[a]	3.9	42	30.5[a]	3.2			
Chambers	2	24	26.2[a]	3.7	25	26.5[a]	3.9			
Means		63	29.1[a]	2.8	67	29.0[a]	2.5	130	29.0[a]	1.8
FACE[4]		37	45.1[b]	5.0	24	39.5[b]	5.8	61	43.0	3.8

1 Neonate larval to pupal stage, males and females pooled.

2 650 and 522 μℓ/liter for the chambers and FACE plots, respectively.

3 360 μℓ/liter

4 Field plot with free-air CO_2 enrichment.

a,b Means in each column or row followed by the same letter are not significantly different ($P > 0.05$). Means followed by a different letter are significantly different ($P < 0.001$) by ANOVA and Duncans' multiple range test.

Table 32. Carbon and nitrogen values for seed from cotton grown in enriched and ambient carbon dioxide atmospheres[1].

Sample	Carbon[2]		Nitrogen[2]		C:N ratio
	% ±	SEM	% ±	SEM	
Chambers					
CO_2, immature	45.05	0.70	3.38	0.06	13.33[a]
Ambient, immature	48.34	1.08	3.76	0.04	12.86[a]
CO_2, mature	45.13	0.23	4.59	0.06	9.83[b]
Ambient, mature	47.43	0.56	4.30	0.09	11.03[b]
FACE[3]					
CO_2, mature	46.97	0.78	3.53	0.13	13.31[a]
Ambient, Mature	49.70	1.16	3.58	0.03	13.88[a]

1 650 and 522 µℓ/liter for the chambers and FACE plots, respectively. Ambient CO_2 was 360 µℓ/liter.

2 No. obs. for carbon was 5. No. obs. for nitrogen was 3.

3 Field plot with free-air CO_2 enrichment.

a,b Means in each column followed by a different letter are significantly different ($P < 0.05$) by ANOVA and Duncans' multiple range test.

Table 33. Irrigation and rain amounts for the FIZZ/FACE 86 experiment.

Date	Day of Year	Irrig. (I) or Rain (R)	FACE + CONTROL				FIZZ	
			REP I	REP II	REP III	REP IV	Irrig. Amount	CO_2 time*
			- - - - - - - - mm - - - - - - -				mm	hr
7 May	127	I	150.0	150.0	150.0	150.0	150.0	
29 May	149	I	36.6	36.6	36.6	36.6	36.6	
1 Jun	152	R	0.5	0.5	0.5	0.5	0.5	
11 Jun	162	I	10.7	12.4	11.0	9.8	11.0	
12 Jun	163	I	10.7	12.4	11.0	9.8	11.0	
13 Jun	164	I	10.7	12.4	11.0	9.8	11.0	
14 Jun	165	I	10.7	12.4	11.0	9.8	11.0	
15 Jun	166	I	10.7	12.4	11.0	9.8	11.0	
16 Jun	167	I	10.7	12.4	11.0	9.8	11.0	
18 Jun	169	I	19.4	18.7	22.4	25.5	21.5	
19 Jun	170	I	19.4	18.7	22.4	25.5	21.5	
20 Jun	171	I	10.3	8.9	8.2	7.5	8.7	
21 Jun	172	I	10.3	8.9	8.2	7.5	8.7	
22 Jun	173	I	10.3	8.9	8.2	7.5	8.7	
23 Jun	174	I	10.3	8.9	8.2	7.5	8.7	
25 Jun	176	I	11.8	13.3	11.1	7.6	11.0	
26 Jun	177	I	11.8	13.3	11.1	7.6	11.0	
27 Jun	178	I	11.8	13.3	11.1	7.6	11.0	
28 Jun	179	I	11.8	13.3	11.1	7.6	11.0	
29 Jun	180	I	11.8	13.3	11.1	7.6	11.0	
30 Jun	181	I	11.8	13.3	11.1	7.6	11.0	
1 Jul	182	R	10.9	10.9	10.9	10.9	10.9	
2 Jul	183	R	14.0	14.0	14.0	14.0	14.0	
2 Jul	183	I					17.3	5.77
3 Jul	184	I					17.3	5.77
4 Jul	185	R	1.3	1.3	1.3	1.3	1.3	
4 Jul	185	I					17.3	5.77
5 Jul	186	I	16.1	17.0	16.6	24.8	17.3	5.77
6 Jul	187	I	16.1	8.9	16.7	24.8	10.7	3.57
7 Jul	188	I	16.1	8.9	16.7	24.8	10.7	3.57
9 Jul	190	I	14.9	12.8	15.6	15.3	10.7	3.57
10 Jul	191	I	14.9	12.8	15.6	15.3	10.7	3.57
11 Jul	192	I	14.9	12.8	15.6	15.3	10.7	3.57
12 Jul	193	I	14.9	12.8	15.6	15.3	10.7	3.57
13 Jul	194	I	14.9	12.8	15.6	15.3	10.7	3.57
14 Jul	195	I	14.9	12.8	15.6	15.3	10.7	3.57
16 Jul	197	I	10.4	13.3	9.8	11.1	12.7	4.23
17 Jul	198	I	10.4	13.3	9.8	11.1	12.7	4.23
18 Jul	199	I	10.4	13.3	9.8	11.1	12.7	4.23

Table 33. (contd.) Irrigation and rain amounts for the FIZZ/FACE 86 experiment.

Date	Day of Year	Irrig. (I) or Rain (R)	FACE + CONTROL REP I	REP II	REP III	REP IV	FIZZ Irrig. Amount	FIZZ CO_2 time*
			mm	mm	mm	mm	mm	hr
19 Jul	200	I	10.4	13.3	9.8	11.1	12.7	4.23
20 Jul	201	I	10.4	13.3	9.8	11.1	12.7	4.23
21 Jul	202	R	15.2	15.2	15.2	15.2	15.2	
21 Jul	202	I	10.1	13.3	9.8	10.9	12.7	4.23
23 Jul	204	I	13.5	13.3	14.0	13.2	13.1	4.37
24 Jul	205	I	13.5	13.3	14.0	13.2	13.1	4.37
25 Jul	206	I	13.5	13.3	14.0	13.2	13.1	4.37
26 Jul	207	I	13.5	13.3	14.0	13.2	13.1	4.37
27 Jul	208	I	13.5	13.3	14.0	13.2	13.1	4.37
28 Jul	209	I	13.5	13.3	14.0	13.2	13.1	4.37
30 Jul	211	I	11.2	11.9	10.8	11.3	10.8	3.60
31 Jul	212	I	11.2	11.9	10.8	11.3	10.8	3.60
1 Aug	213	I	11.2	11.9	10.8	11.3	10.8	3.60
2 Aug	214	I	11.2	11.9	10.8	11.3	10.8	3.60
3 Aug	215	I	11.2	11.9	10.8	11.3	10.8	3.60
4 Aug	216	I	11.2	11.9	10.6	11.2	10.7	3.60
6 Aug	218	I	13.4	11.1	13.6	13.7	14.0	4.67
7 Aug	219	R	2.8	2.8	2.8	2.8	2.8	
7 Aug	219	I	13.4	11.1	13.6	13.7	14.0	4.67
8 Aug	220	I	13.4	11.1	13.6	13.7	14.0	4.67
9 Aug	221	R	1.1	1.1	1.1	1.1	1.1	
9 Aug	221	I	13.4	11.1	13.6	13.7	14.0	4.67
10 Aug	222	I	13.4	11.1	13.6	13.7	14.0	4.67
11 Aug	223	I	13.4	11.1	13.6	13.7	14.0	4.67
13 Aug	225	I	10.0	9.8	9.8	10.0	12.1	4.03
14 Aug	226	I	10.0	9.8	9.8	10.0	12.1	4.03
15 Aug	227	I	10.0	9.8	9.8	10.0	12.1	4.03
16 Aug	228	I	10.0	9.8	9.8	10.0	12.1	4.03
17 Aug	229	I	10.0	9.8	9.8	10.0	12.1	4.03
18 Aug	230	I	9.9	10.0	9.8	10.0	12.1	4.03
20 Aug	232	I	19.4	44.4	32.0	16.9	16.5	5.50
21 Aug	233	I	25.6	18.3	18.9	23.1	16.8	5.60
22 Aug	234	I	25.6	18.3	18.9	23.1	16.8	5.60
23 Aug	235	I	25.6	18.3	18.9	23.1	16.8	5.60
24 Aug	236	I	25.6	18.3	18.9	23.1	16.8	5.60
25 Aug	237	R	0.5	0.5	0.5	0.5	0.5	
25 Aug	237	I	25.7	18.2	18.8	23.1	16.8	5.60
26 Aug	238	R	5.3	5.3	5.3	5.3	5.3	
27 Aug	239	R	23.1	23.1	23.1	23.1	23.1	

Table 33. (contd.) Irrigation and rain amounts for the FIZZ/FACE 86 experiment.

Date	Day of Year	Irrig. (I) or Rain (R)	FACE + CONTROL				FIZZ	
			REP I	REP II	REP III	REP IV	Irrig. Amount	CO_2 time*
			mm				mm	hr
27 Aug	239	I	11.3	6.8	0	0	10.8	3.60
28 Aug	240	R	0.8	0.8	0.8	0.8	0.8	
29 Aug	241	R	2.0	2.0	2.0	2.0	2.0	
29 Aug	241	I	4.4	8.2	12.3	10.3	7.5	2.50
30 Aug	242	I	4.4	8.2	12.3	10.3	7.5	2.50
31 Aug	243	I	4.4	8.2	12.3	10.3	7.5	2.50
1 Sep	244	I	4.4	8.2	12.3	10.3	7.5	2.50
3 Sep	246	I	8.5	11.5	9.5	8.7	8.3	2.77
4 Sep	247	I	12.6	13.0	24.4	9.4	8.3	2.77
5 Sep	248	I	12.6	13.0	24.4	9.4	8.3	2.77
6 Sep	249	I	12.6	13.0	24.4	9.4	8.3	2.77
7 Sep	250	I	12.6	13.0	24.4	9.4	8.3	2.77
8 Sep	251	I	0.0	0.0	0.0	9.5	8.3	2.77
10 Sep	253	I	9.2	12.5	4.8	12.1	17.8	5.93
11 Sep	254	I	9.2	12.5	4.8	12.1	17.8	5.93
12 Sep	255	I	9.2	12.5	4.8	12.1	17.8	5.93
13 Sep	256	I	9.2	12.5	4.8	12.1	17.8	5.93
14 Sep	257	I	9.2	12.5	4.8	12.1	17.8	5.93
15 Sep	258	I	9.2	12.5	4.8	12.1	17.8	5.93
17 Sep	260	I	11.4	9.8	20.4	9.7	7.6	2.53
18 Sep	261	I	11.4	9.8	20.4	9.7	7.6	2.53
19 Sep	262	I	11.4	9.8	20.4	9.7	7.6	2.53
20 Sep	263	I	11.4	9.8	20.4	9.7	7.6	2.53
21 Sep	264	I	11.4	9.8	20.4	9.7	7.6	2.53
22 Sep	265	I	11.4	9.8	20.4	9.7	7.6	2.53
23 Sep	266	R	9.7	9.7	9.7	9.7	9.7	
25 Sep	268	R	0.5	0.5	0.5	0.5	0.5	
		Totals	1336.8	1342.1	1410.3	1341.1	1358.0	291.52

* based on an average flow rate of 3 mm/hr

Table 34. pH of untreated and carbonated irrigation water and also of the soil at various times during an irrigation that started at 08:30.

	Irrigation Water		Soil	
Time	Check	CO_2-treated	Check	CO_2-treated
0830	7.47	5.05	8.03	5.80
0940	7.63	5.16	7.50	5.83
1130	7.49	5.11	7.40	6.17
1300	7.52	5.13	7.55	5.98

Table 35. Mean CO_2 concentrations and the associated standard deviations at the 75% plant height from 21 June through 28 September for the 1986 FIZZ/FACE experiment at Phoenix, Arizona.

Rep	CONTROL	FIZZ	FACE
		µℓ/ℓ	
Daytime:			
I	354 ± 43	360 ± 46	538 ± 208
II	361 ± 68	362 ± 53	535 ± 388
III	368 ± 83	373 ± 83	539 ± 298
IV	357 ± 47	361 ± 56	475 ± 150
Average	360 ± 63	364 ± 61	522 ± 233
Nighttime:			
I	382 ± 46	383 ± 46	386 ± 55
II	376 ± 43	373 ± 53	388 ± 65
III	388 ± 54	390 ± 57	398 ± 123
IV	387 ± 54	384 ± 52	391 ± 78
Average	383 ± 50	383 ± 50	391 ± 84
Whole Day:			
I	368 ± 47	371 ± 48	464 ± 17
II	368 ± 57	368 ± 48	463 ± 194
III	378 ± 71	381 ± 72	469 ± 240
IV	372 ± 53	372 ± 55	433 ± 128
Average	371 ± 58	373 ± 57	457 ± 188

Table 36. Mean CO_2 concentrations and the associated standard deviations at various heights for Rep IV from 21 June through 28 September for the 1986 FIZZ/FACE experiment at Phoenix, Arizona.

Height[a]	CONTROL	FIZZ	FACE
	TREATMENT		
	- - - - - - μℓ/ℓ - - - - - -		
Daytime:			
1.8 m	358 ± 41	356 ± 40	370 ± 45
75%	357 ± 47	361 ± 56	475 ± 150
50%	359 ± 50	369 ± 85	564 ± 265
25%	362 ± 53	383 ± 139	702 ± 414
Nighttime:			
1.8 m	370 ± 43	368 ± 43	368 ± 41
75%	387 ± 54	384 ± 52	391 ± 78
50%	390 ± 56	390 ± 56	404 ± 120
25%	394 ± 56	394 ± 58	412 ± 149
Whole Day:			
1.8 m	364 ± 42	362 ± 42	369 ± 43
75%	372 ± 53	372 ± 55	433 ± 128
50%	374 ± 55	380 ± 73	485 ± 222
25%	377 ± 57	388 ± 107	560 ± 345

[a] % of plant height or 1.8 m

Table 37. Final harvest data from the open field CO_2-release (FIZZ/FACE) studies. Data are averages of 5 m^2 harvested on October 5-10, 1986 (day 278-283) for each of the four replications.

TREATMENT REPLICATION	Control (C)				Fizz (Z)				Free-Air (A)			
	I	II	III	IV	I	II	III	IV	I	II	III	IV
Plants/m^2	9	10	10	9	9	10	11	9	10	10	9	11
Plant Height (cm)	79	85	76	64	77	82	63	72	77	77	66	73
Bolls/m^2	103	134	81	109	105	110	81	120	111	111	91	119
Top Dry Wt. (g/m^2)	705	969	441	624	743	740	503	788	851	793	642	856
Root Dry Wt. (g/m^2)	46	58	38	40	55	43	40	37	57	62	57	54
Biomass (g/m^2)	751	1027	479	664	798	783	543	825	908	855	699	910
Ave. Biomass (g/m^2)		721				737				843		
Rel. CO_2 Effect		1.00				1.02				1.17		
Lint Wt. (g/m^2)	118	146	75	112	145	138	97	123	160	159	128	147
Seed Wt. (g/m^2)	180	224	111	157	214	231	134	169	240	245	183	213
Average Open Seed Cotton (g/m^2)		281				313				369		
Rel. CO_2 Effect		1.00				1.11				1.31		
Percent Lint (%)	40	39	40	42	40	37	42	42	40	39	41	41
Total Seed Cotton[1]	391	522	246	426	419	141	282	479	439	433	356	501
Average (g/m^2)		396				399				432		
Rel. CO_2 effect		1.00				1.01				1.09		
Harvest Index[2] (%)	55	54	56	68	56	56	56	61	52	55	55	58

[1] Includes estimate of seed cotton in green bolls at the time of harvest (g/m^2)
[2] Seed cotton weight/Top dry weight X 100.

Table 38. Final harvest data of the open-field release (FIZZ/FACE) study when Replication II was deleted from the averages. Data are averages of three replications.

Treatment	Control	Fizz (Z)	Free-air (A)
Total Biomass (g/m^2)	631	722	839
Relative CO_2 Effect	1.00	1.14	1.33
Open Seed Cotton (g/m^2)	251	294	357
Relative CO_2 Effect	1.00	1.17	1.42
Total Seed Cotton (g/m^2)	354	393	432
Relative CO_2 Effect	1.00	1.11	1.22

Table 39. Leaf area per square meter (LAI) and leaf area per active boll ratio (LA/B) of the open-field release (FIZZ/FACE) study. Data are averages of four replications.

TREATMENT	Control (C)		Fizz (Z)		Free-air (A)	
Julian date	LAI	LA/B	LAI	LA/B	LAI	LA/B
168	1.32	880	1.54	857	1.07	1189
175	1.58	299	1.91	298	1.61	537
182	1.89	278	2.50	324	2.56	414
189	2.31	199	2.72	235	2.93	248
196	2.41	225	3.02	343	3.60	238
203	2.53	320	3.18	255	3.86	297
210	2.75	398	2.85	336	3.07	292
216	2.78	507	3.29	417	3.50	479
224	2.42	1066	3.62	1871	3.62	861
231	2.25	1466	3.36	1868	3.26	1715
245	3.82	1365	2.14	1071	2.82	1175
252	2.70	370	2.40	471	2.87	551
259	3.75	338	2.69	672	3.20	916

Table 40. Mean net photosynthesis and stomatal conductance observed during the 1986 FIZZ/FACE experiment. The means are averages over 3 leaves per plot, 4 replicate plots, and 10 days for the "before 10 Sep" values or 2 days for the "after 10 Sep."

Item	Portion of Season	TREATMENT Control	FIZZ	FACE
Net Photosynthesis (μmole m^{-2} s^{-1}):				
	before 10 Sep	23.6A (1.00)	23.5A (1.00)	25.7B (1.09)
	after 10 Sep	18.0A	16.8A	19.6A
Stomatal Conductance (cm s^{-1})				
	before 10 Sep	2.70AB (1.00)	2.79A (1.03)	2.43B (0.90)
	after 10 Sep	1.10A	0.95A	0.99A

Table 41. Mean starch content of cotton leaves in the 1986 FIZZ/FACE experiment. Leaves were sampled at sunrise and sunset, once per week during the experiment. Data were transformed logarithmically prior to split-plot analysis, following a test of homogeneity of variance which indicated the necessity of such a transformation. Means not followed by the same letter in a group of three are statistically different (0.05).

SAMPLING TIME	TREATMENT		
	CONTROL	FIZZ	FACE
	$g\ m^{-2}$		
Sunrise	4.7a	4.3a	6.7b
Sunset	9.4a	9.9a	13.2b
Change (PM - AM)	4.7	5.6	6.5

Table 42. Mean leaf water potentials (LWP) and relative leaf water contents (RLWC) for the 1986 FIZZ/FACE experiment. The number of observations per mean is 4 (reps) times the number of sampling days during the season. None of the differences between treatments were significant at the 0.05 probability level from an F test, which considered repeated measures as subsampling.

SAMPLING TIME	NO. OBS.	TREATMENT CONTROL	FIZZ	FACE
Leaf Water Potential (MPa):				
Predawn	120	-1.08	-1.07	-1.03
Afternoon	120	-1.60	-1.63	-1.58
Relative Leaf Water Content (%):				
Predawn	112	85.0	87.6	86.5
Afternoon	108	74.4	75.5	76.8
Dry Matter Content (%):				
Predawn	112	19.8	19.0	19.5
Afternoon	108	23.0	22.8	23.1

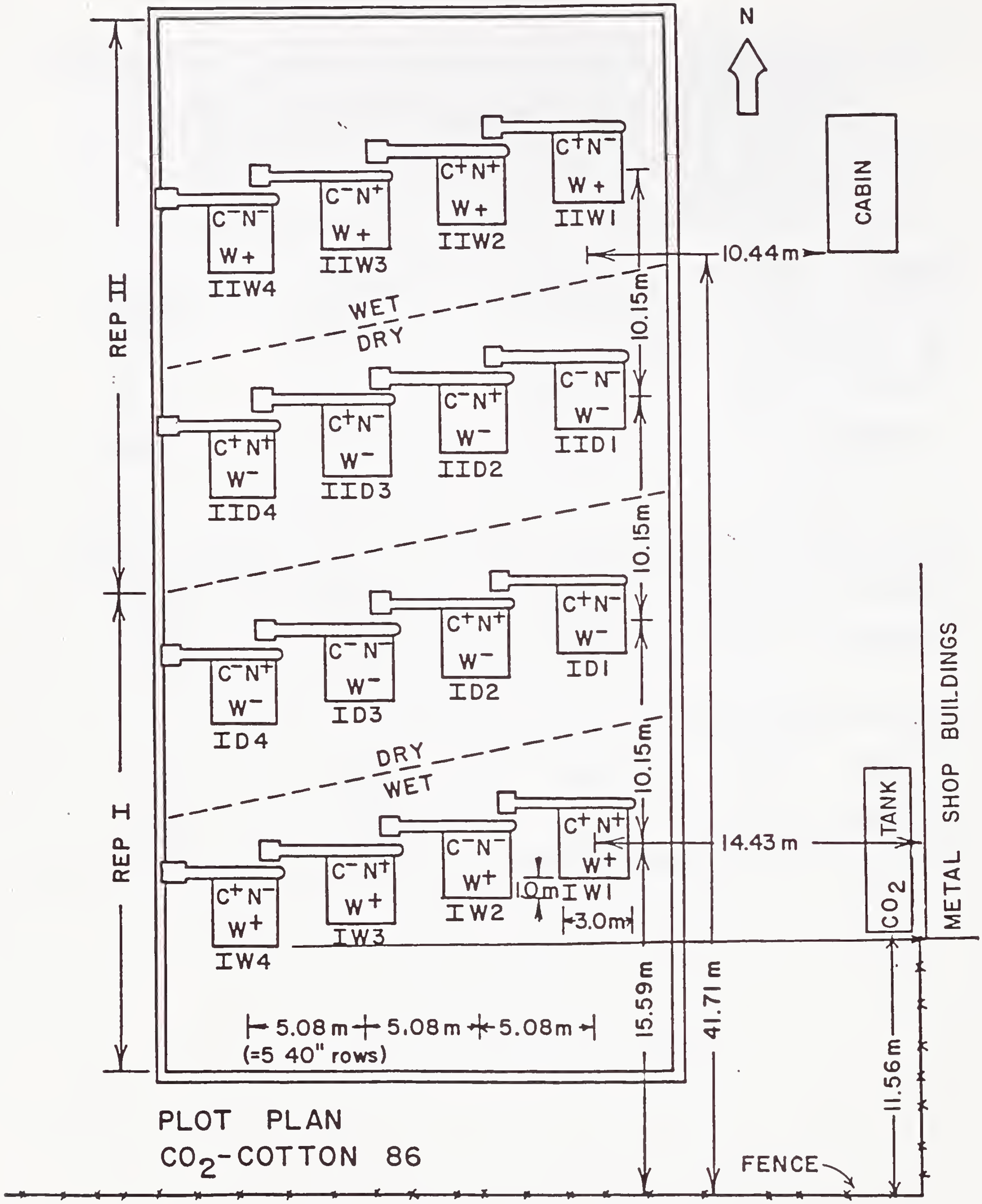

Figure 1. Plot plan for the 1986 CO_2/WATER/NITROGEN experiment showing the arrangement of the open-top chamber plots with 2 reps (I & II), ambient (C^-) and 650 $\mu\ell\ \ell^{-1}$ (C^+) CO_2 treatments, well-watered (W^+) and water stress (W^-) irrigation treatments, and none added (N^-) and added (N^+) nitrogen fertilizer treatments.

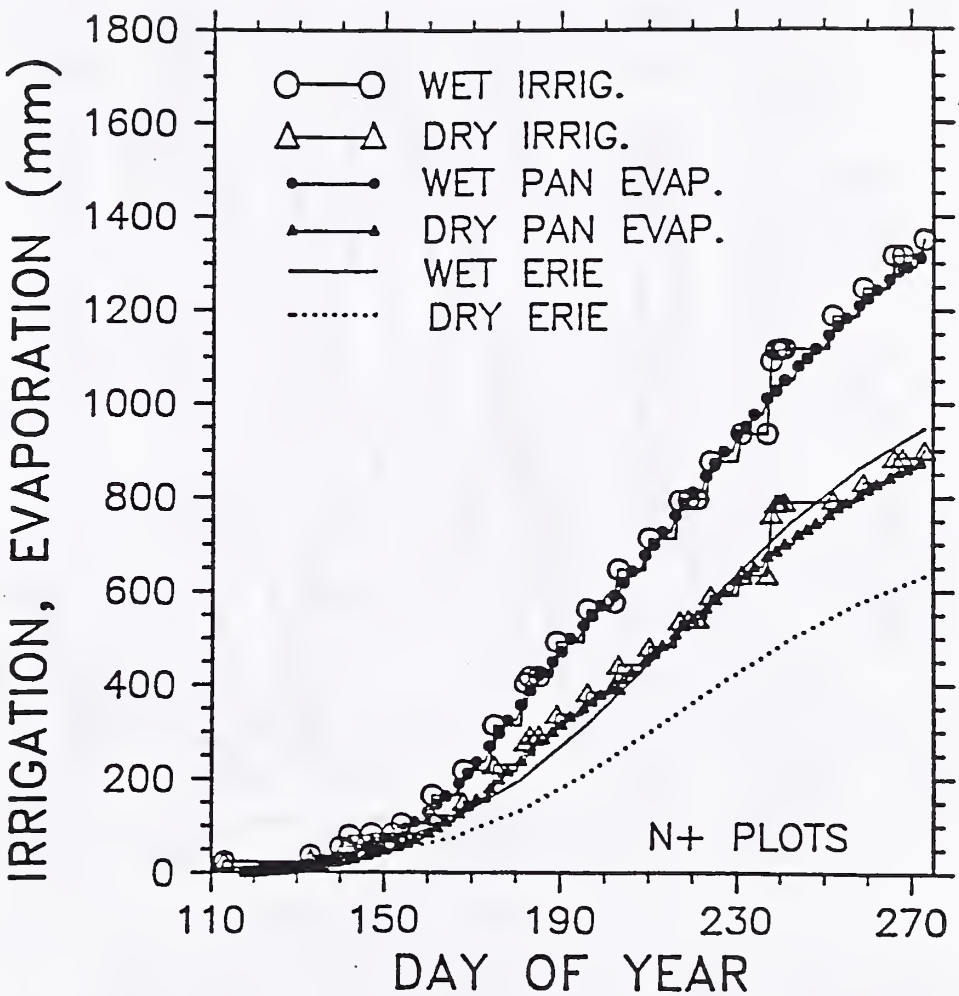

Figure 2. Amounts of irrigation and rainfall applied to the wet and the dry plots that received added nitrogen (N^+) for the CO_2-cotton 1986 experiment. Initial pre-irrigations are not included. Also plotted are the measured pan evaporation (X LAI/3) and the Erie et al. (1981) consumptive use curve for cotton for comparison with the wet plots as well as 2/3 of those amounts for comparison with the dry plots.

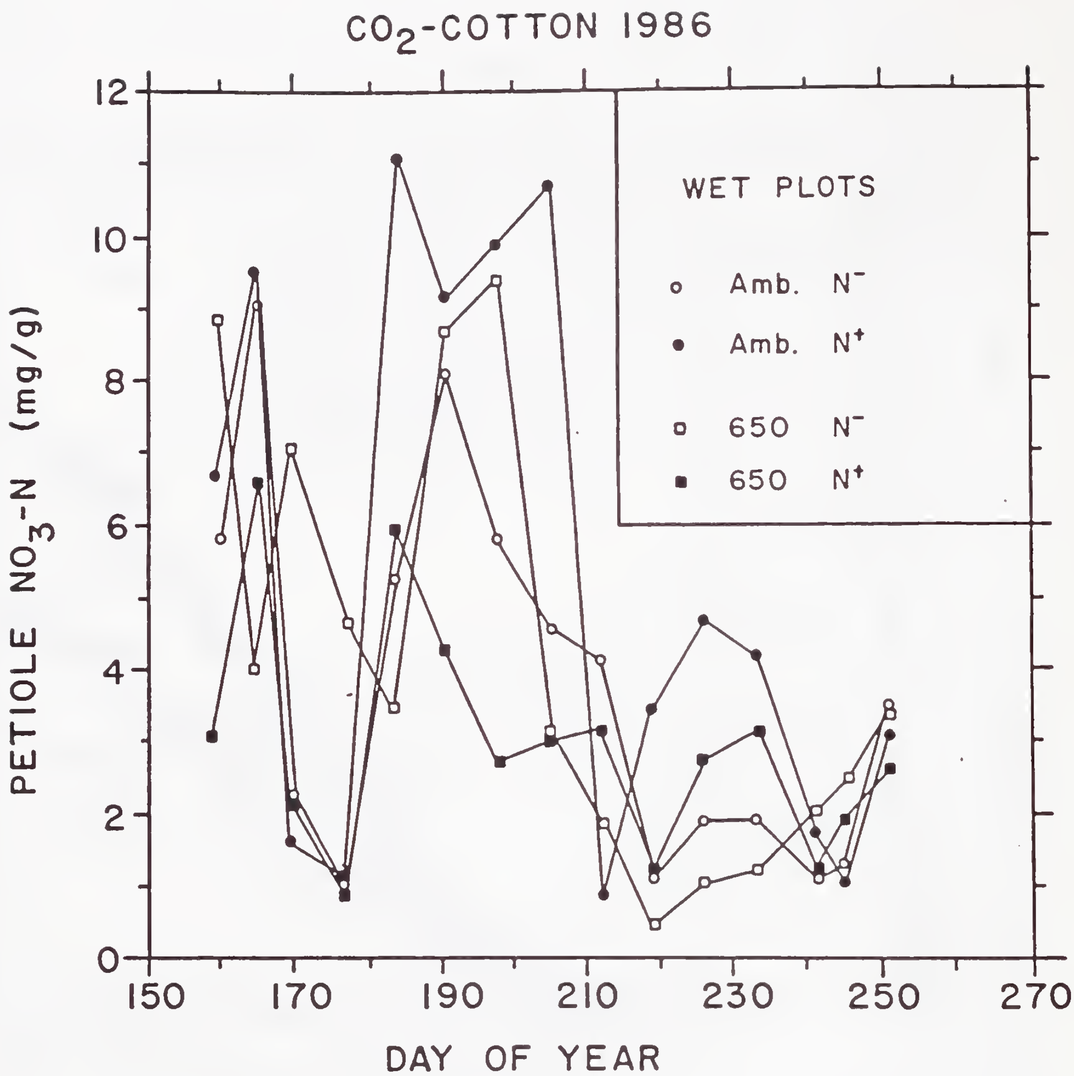

Figure 3. Petiole NO_3-N contents versus day of the year for the ambient CO_2 - low N, ambient CO_2 - high N, 650 μℓ $ℓ^{-1}$ CO_2 - low N, and 650 μℓ $ℓ^{-1}$ CO_2 - high N treatments, all from the wet plots.

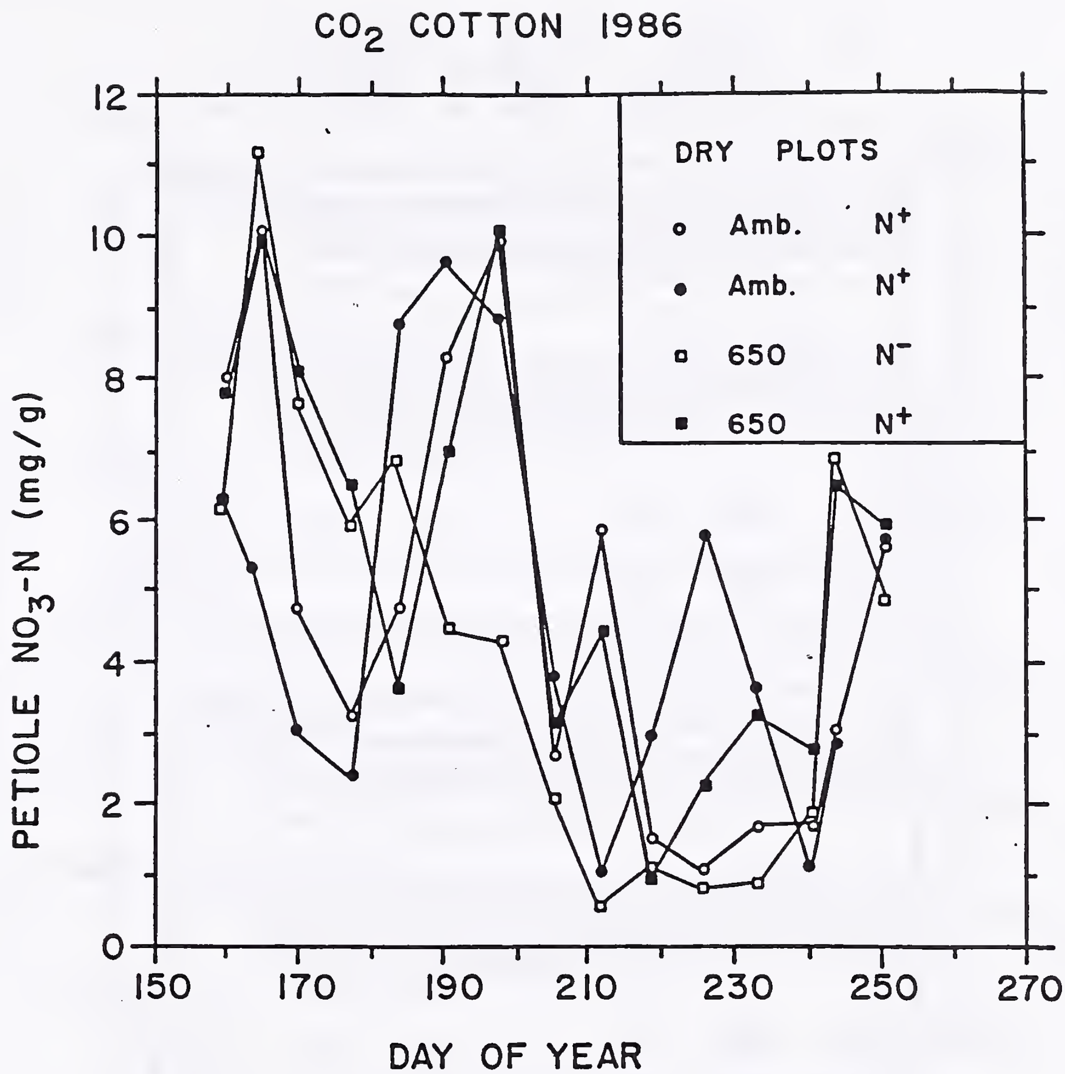

Figure 4. Petiole NO_3-N contents versus day of the year for the ambient CO_2 - low N, ambient CO_2 - high N, 650 $\mu \ell\ \ell^{-1}$ CO_2 - low N, and 650 $\mu \ell\ \ell^{-1}$ CO_2 - high N treatments, all from the dry plots.

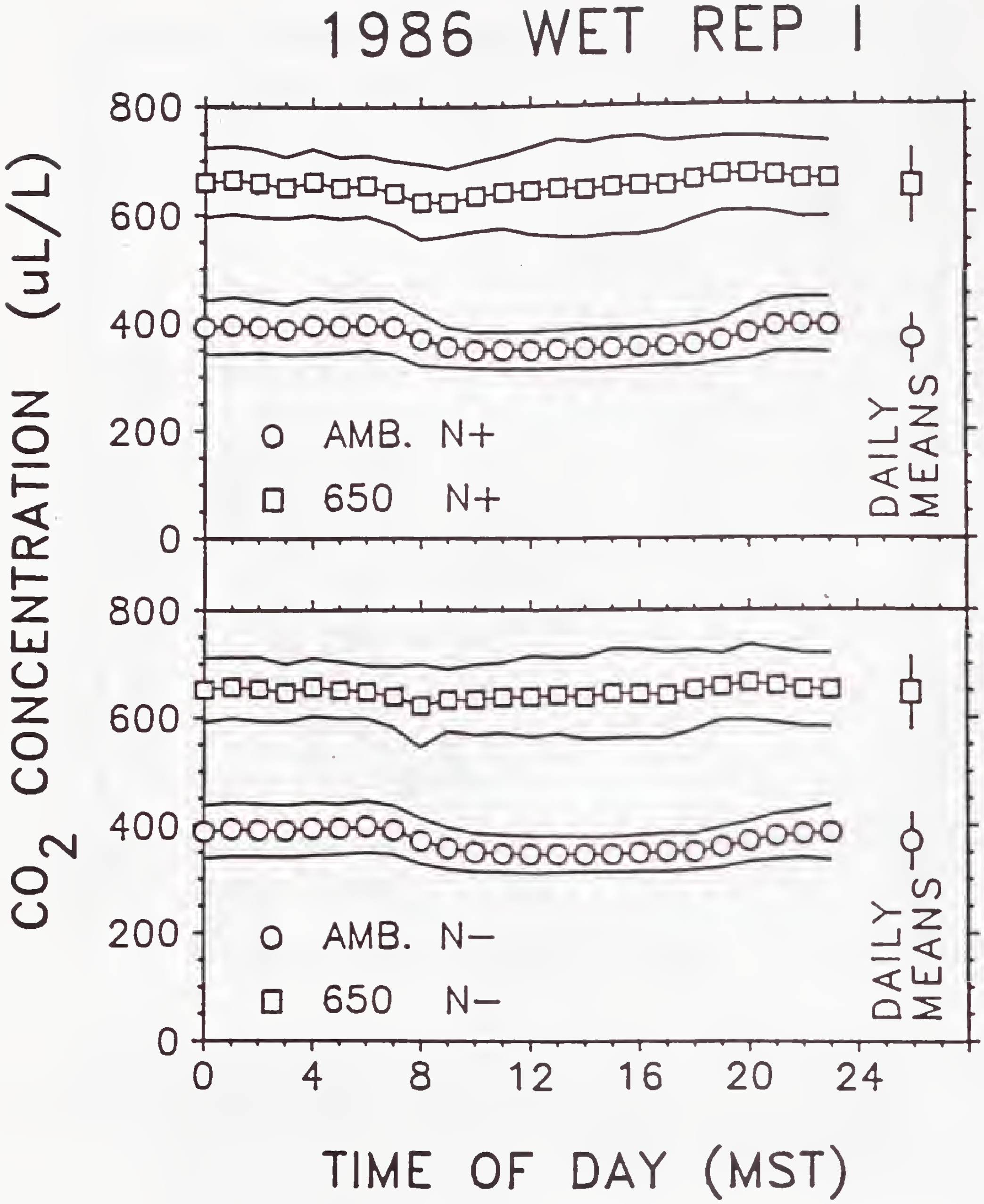

Figure 5. Diurnal pattern of the mean CO_2 concentration for the wet-Rep I chambers in 1986. The upper and lower pairs of solid lines are the standard deviations of the individual observations. On the right are the all-day means and standard deviations.

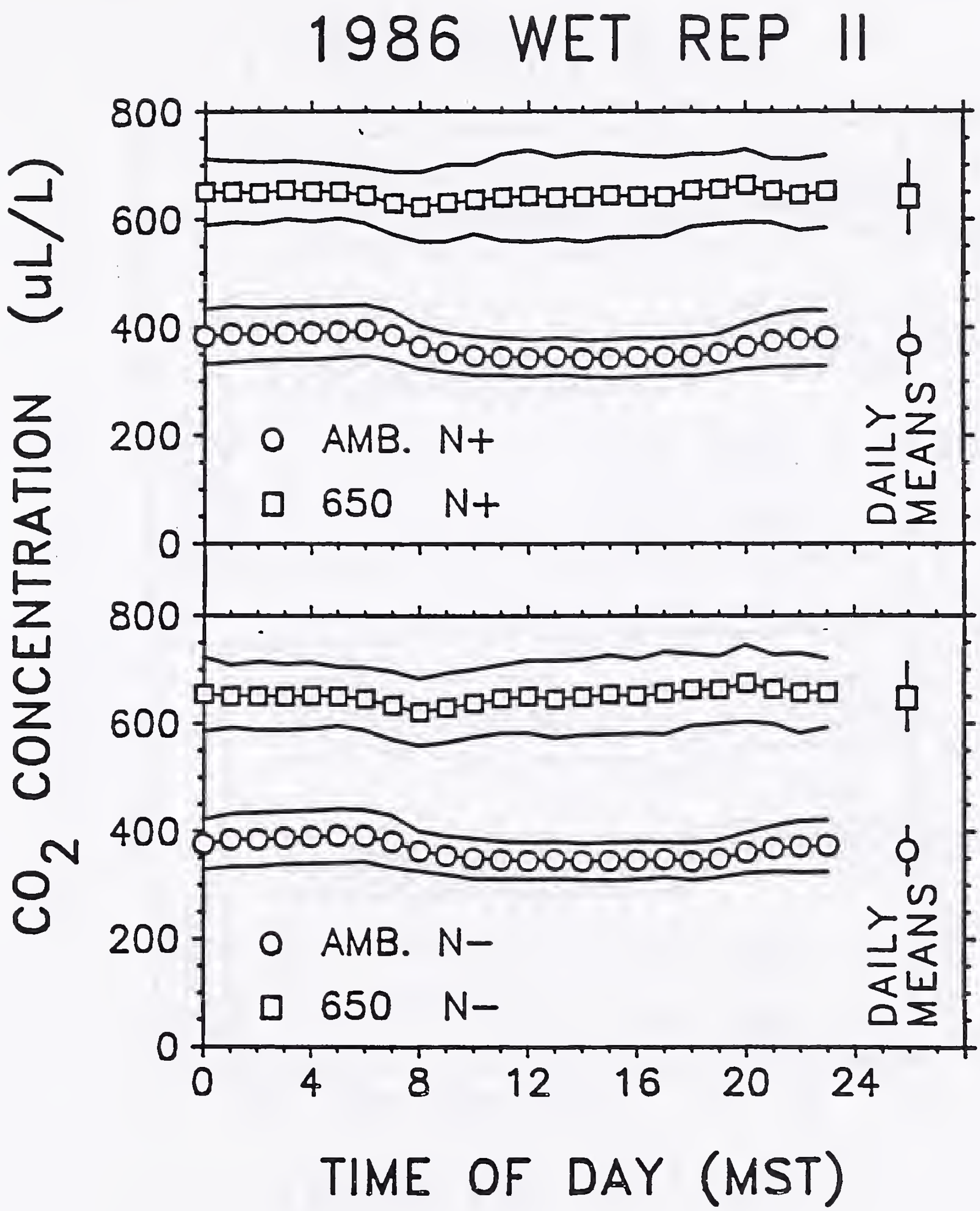

Figure 6. Diurnal pattern of the mean CO_2 concentration for the wet-Rep II chambers in 1986. The upper and lower pairs of solid lines are the standard deviations of the individual observations. On the right are the all-day means and standard deviations.

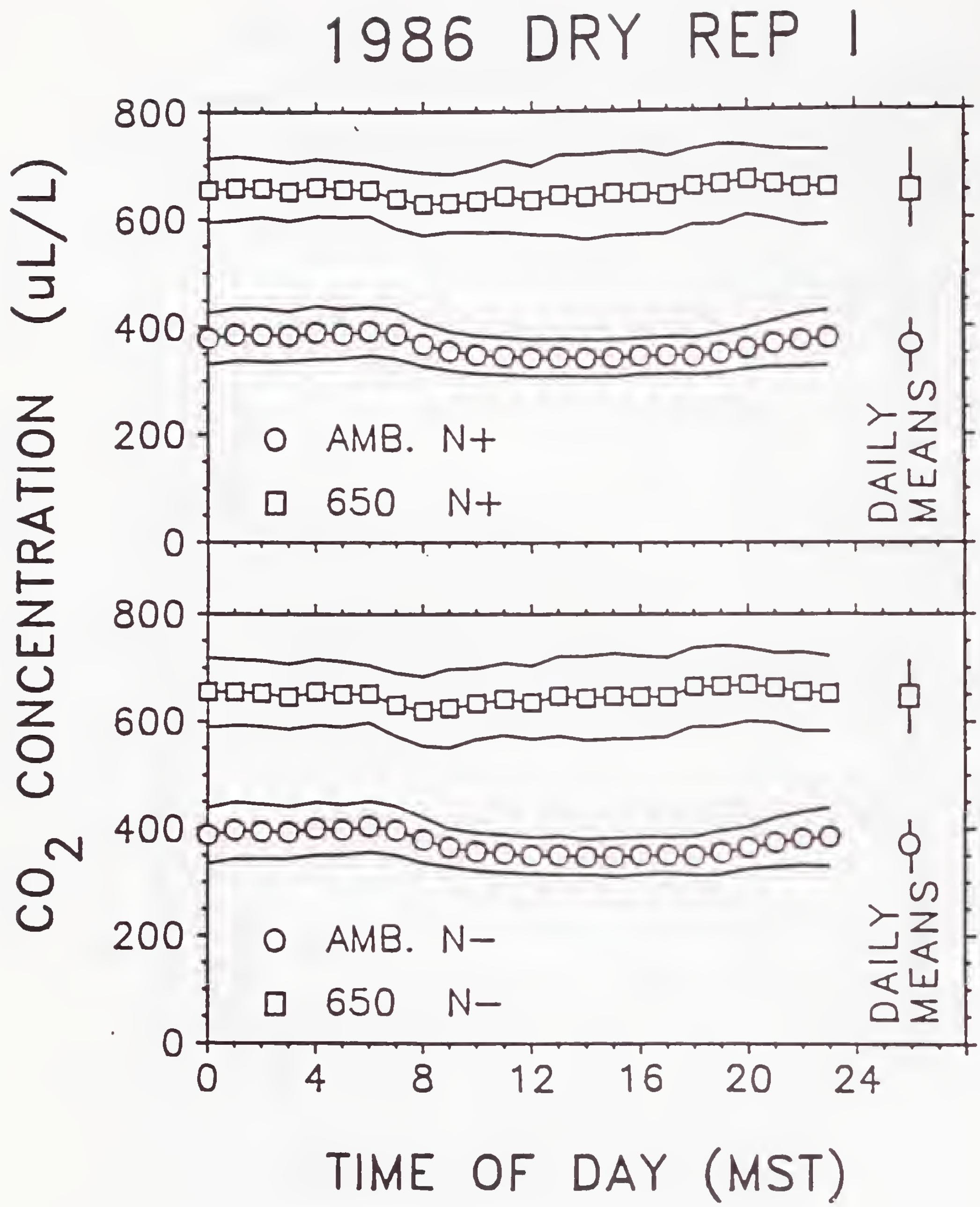

Figure 7. Diurnal pattern of the mean CO_2 concentration for the dry-Rep I chambers in 1986. The upper and lower pairs of solid lines are the standard deviations of the individual observations. On the right are the all-day means and standard deviations.

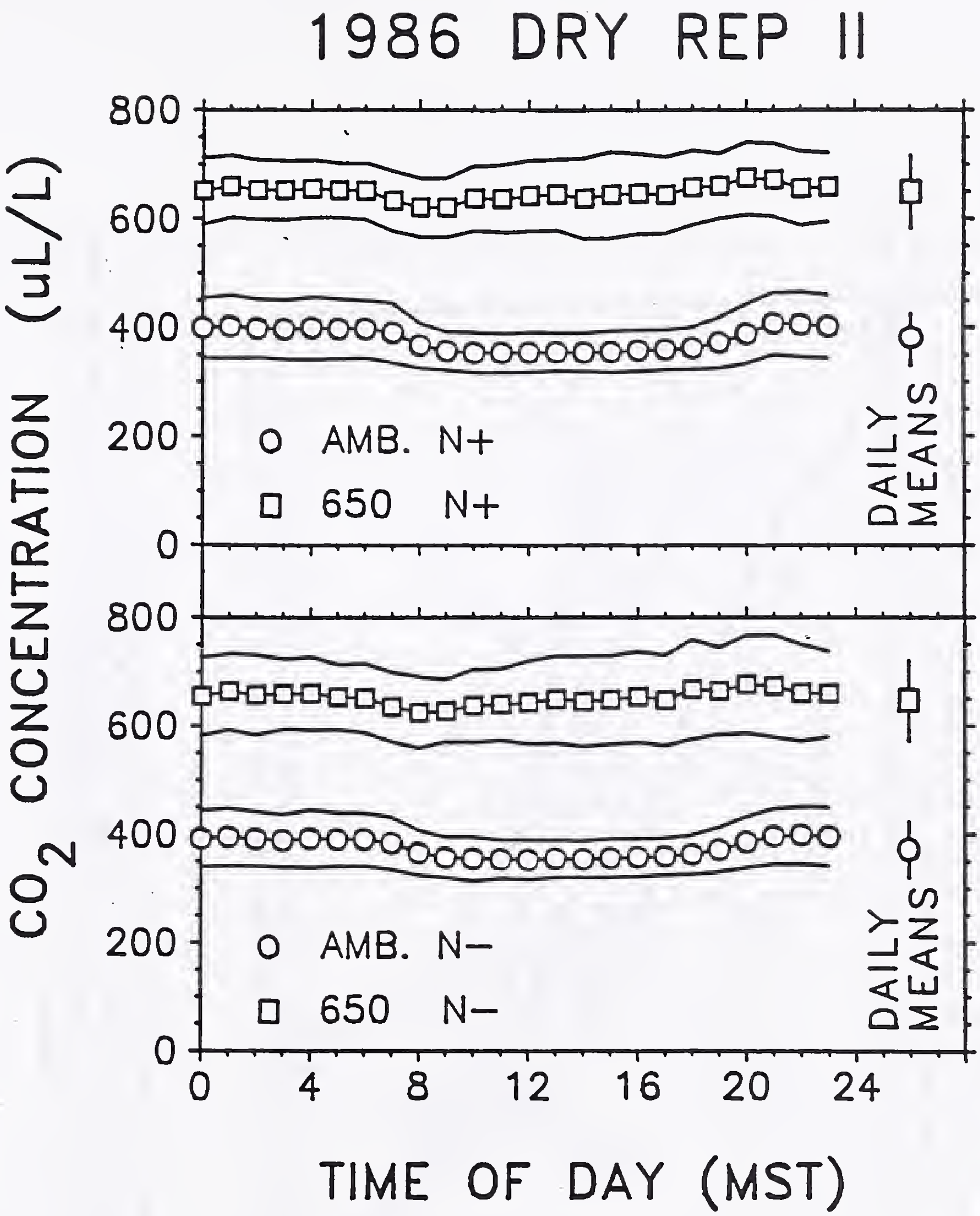

Figure 8. Diurnal pattern of the mean CO_2 concentration for the dry-Rep II chambers in 1986. The upper and lower pairs of solid lines are the standard deviations of the individual observations. On the right are the all-day means and standard deviations.

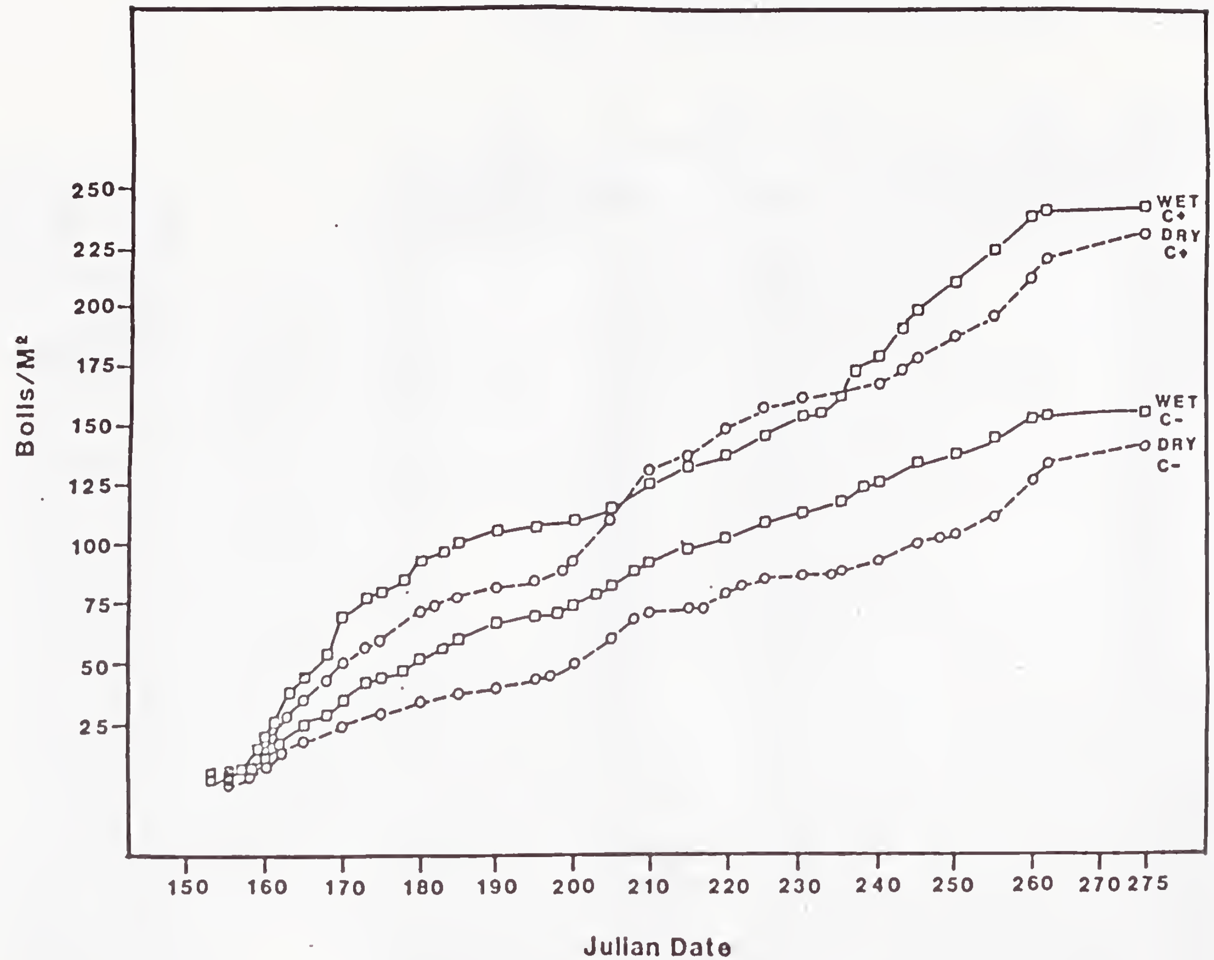

Figure 9. Accumulated boll load in the open-topped enclosures. Data are the average of both high and low nitrogen in the two replications of the Wet-650 ppm CO_2 (Wet C^+) and Dry-650 ppm CO_2 (Dry C^+) and the Wet and Dry ambient chambers (Wet C^- and Dry C^-).

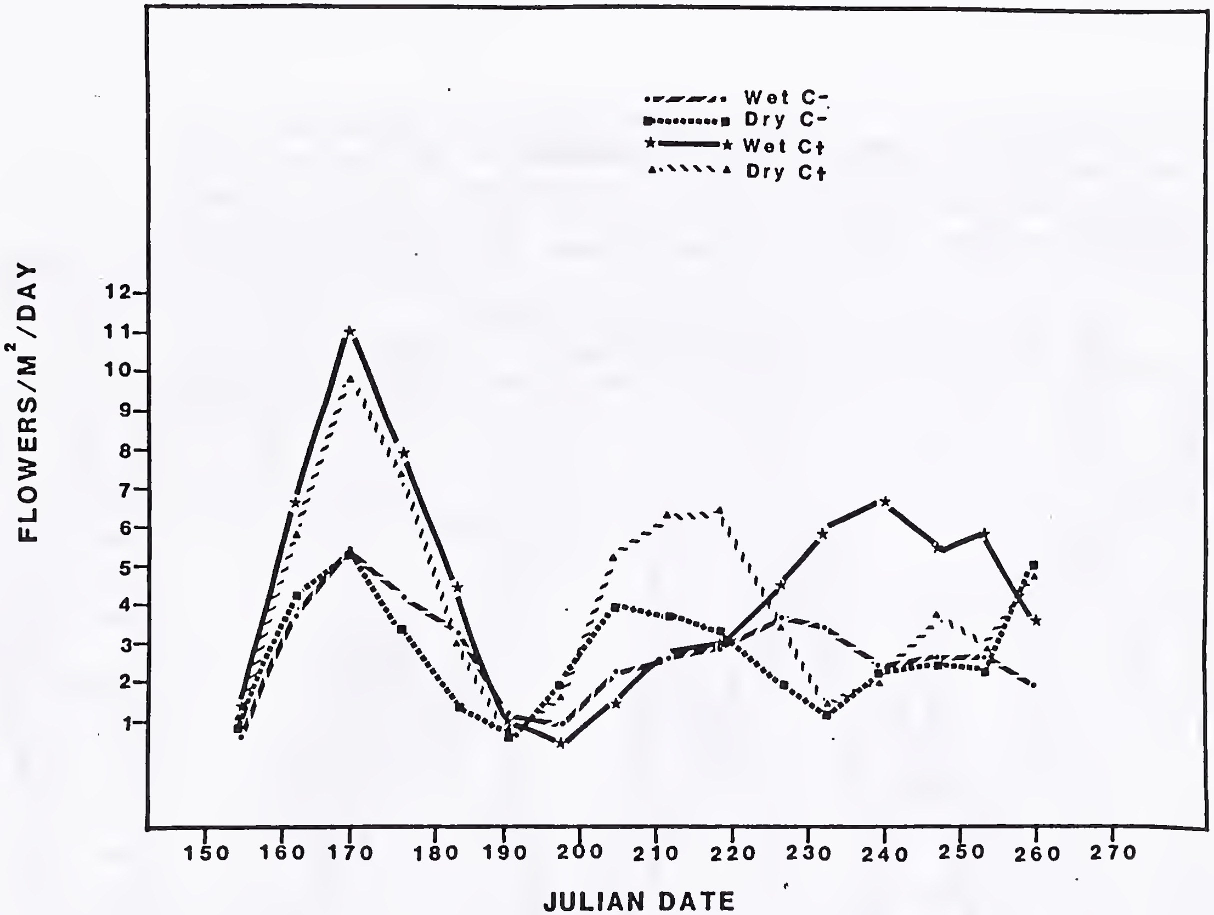

Figure 10. Flowers produced in the open-topped enclosures. Data are the weekly average rate of flowering for the high and low nitrogen treatments of two replications of the 650 ppm CO_2 (C^+) and ambient (C^-) treatments of the Wet and Dry plots.

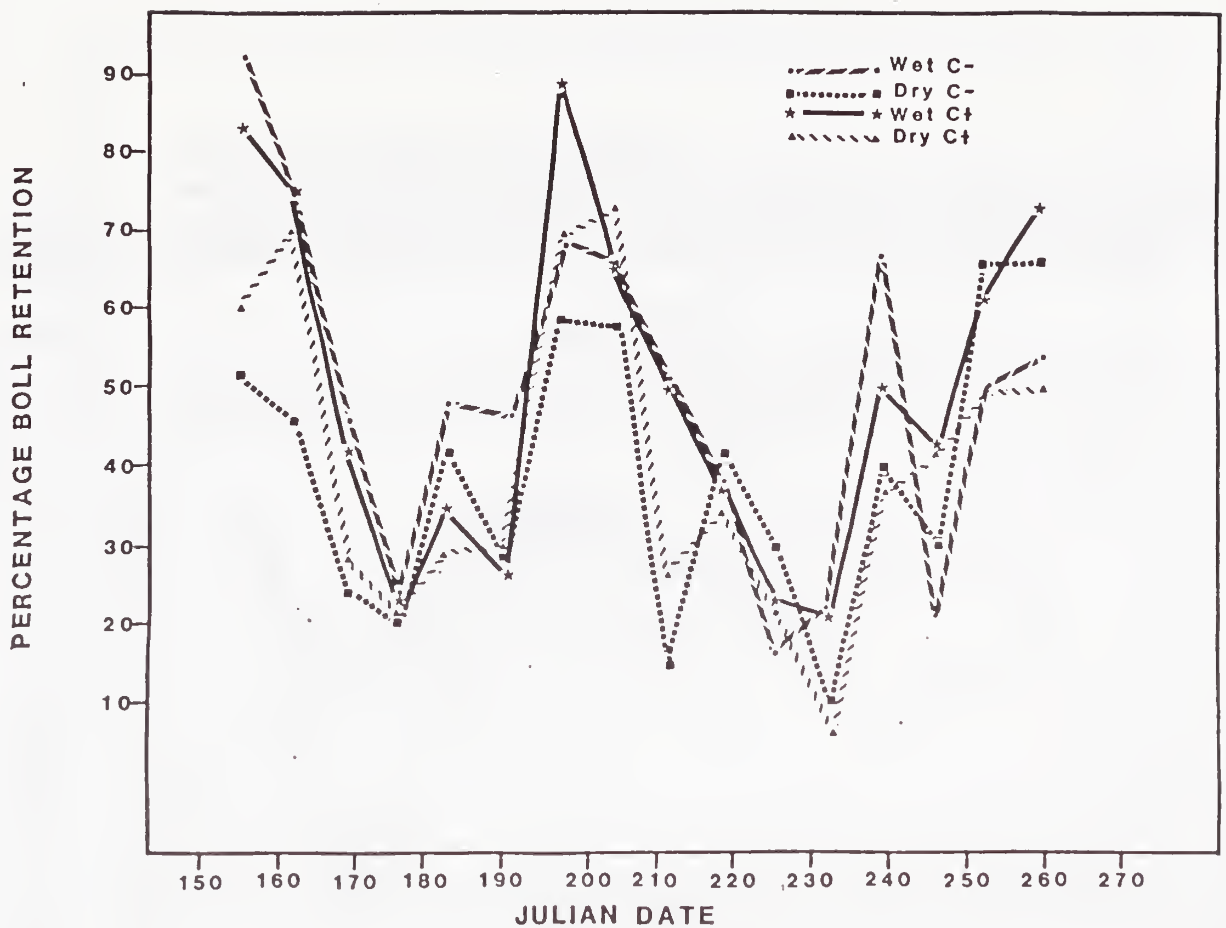

Figure 11. Boll retention in the open-topped enclosures. Data are weekly average percentage of blossoms produced which resulted in harvestable bolls. Averages are of the high and low nitrogen treatments of the two replications of the 650 ppm - CO_2 (C^+) and ambient (C^-) treatments of the Wet and Dry plots.

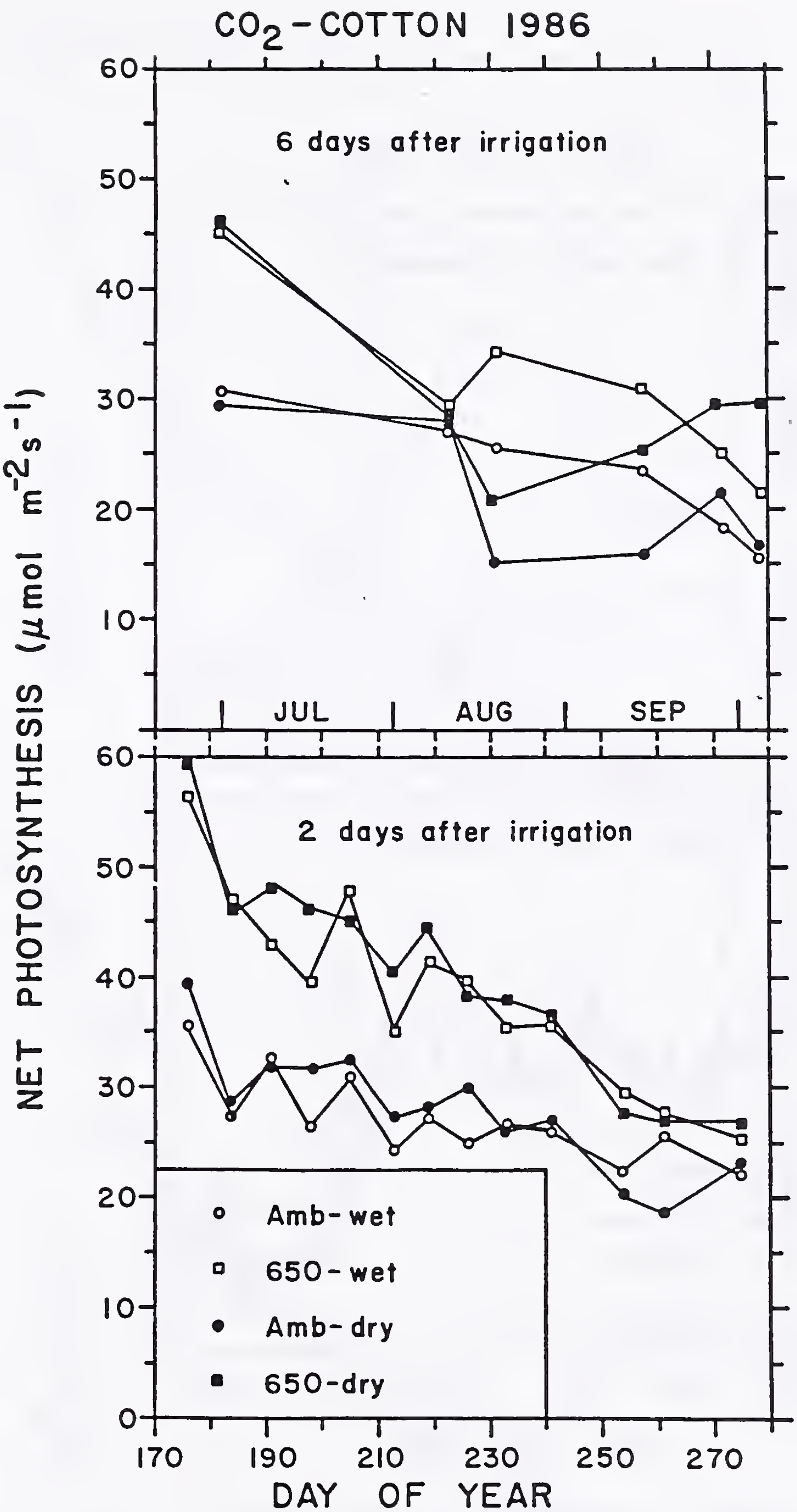

Figure 12. Net photosynthesis of cotton leaves vs day of year for the CO_2-cotton 1986 experiment measured 6 days (upper graph) and 2 days (lower graph) after irrigation. Each data point is an average over 3 leaves per chamber, 2 reps, and 2 nitrogen treatments.

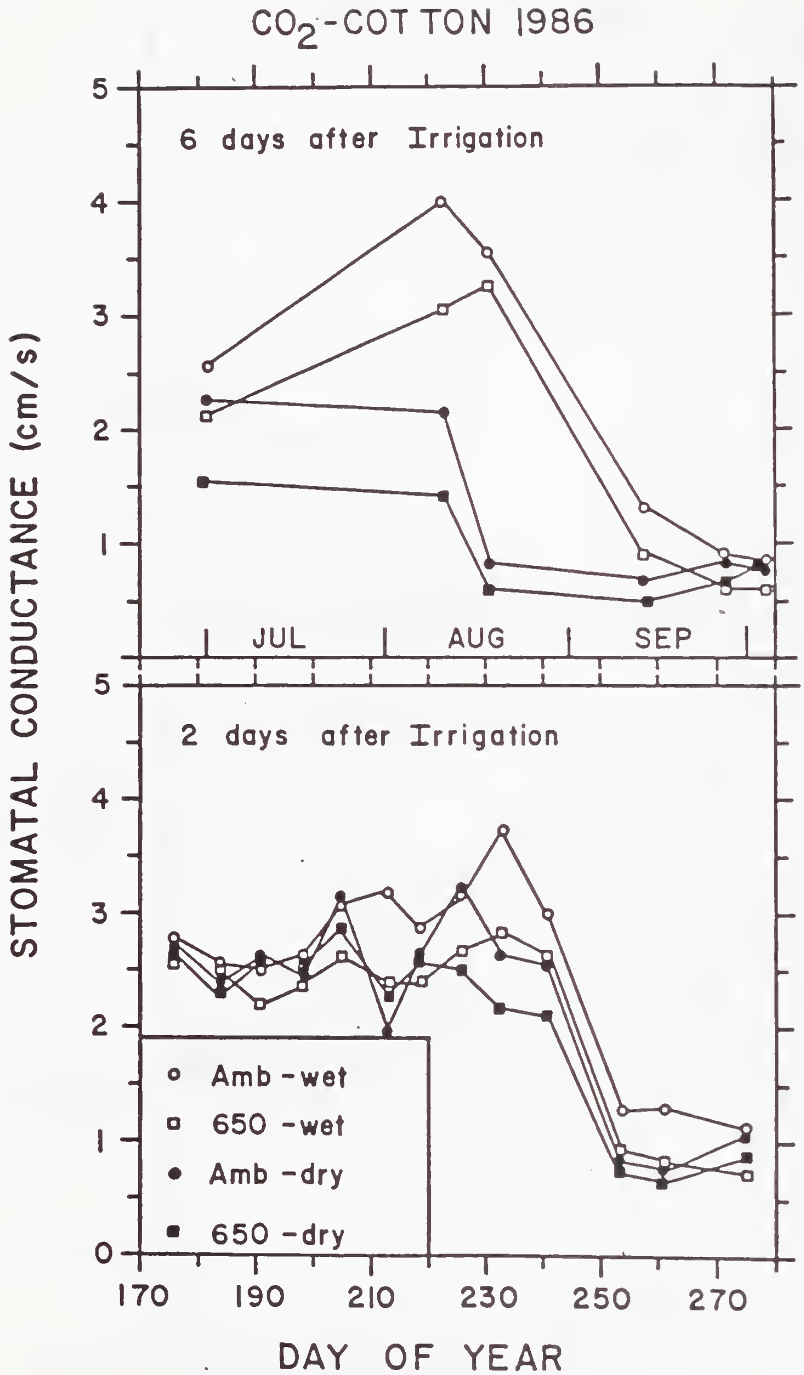

Figure 13. Stomatal conductance of cotton leaves vs day of year for the CO_2-cotton 1986 experiment measured 6 days (upper graph) and 2 days (lower graph) after irrigation. Each point is an average over 3 leaves per chamber, 2 reps, and 2 nitrogen treatments.

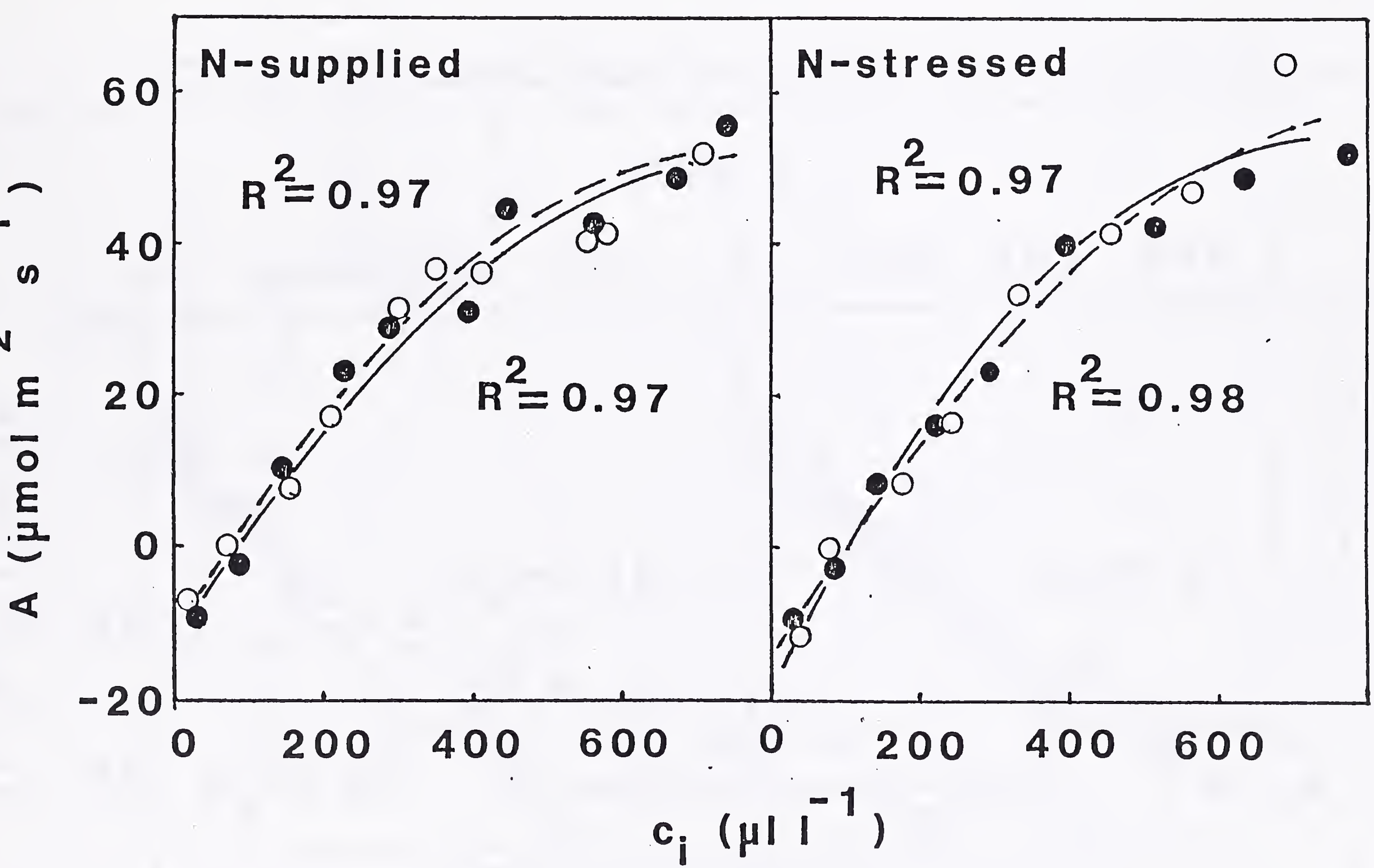

Figure 14. $A(c_i)$ curves for plants grown at ambient CO_2 or enriched CO_2. Left panel: plots fertilized weekly with N. Right panel: no N added. All data shown are from the fully-irrigated treatment. These curves are from data collected on JD 205. o - o, ambient CO_2; ● - - ●, enriched CO_2.

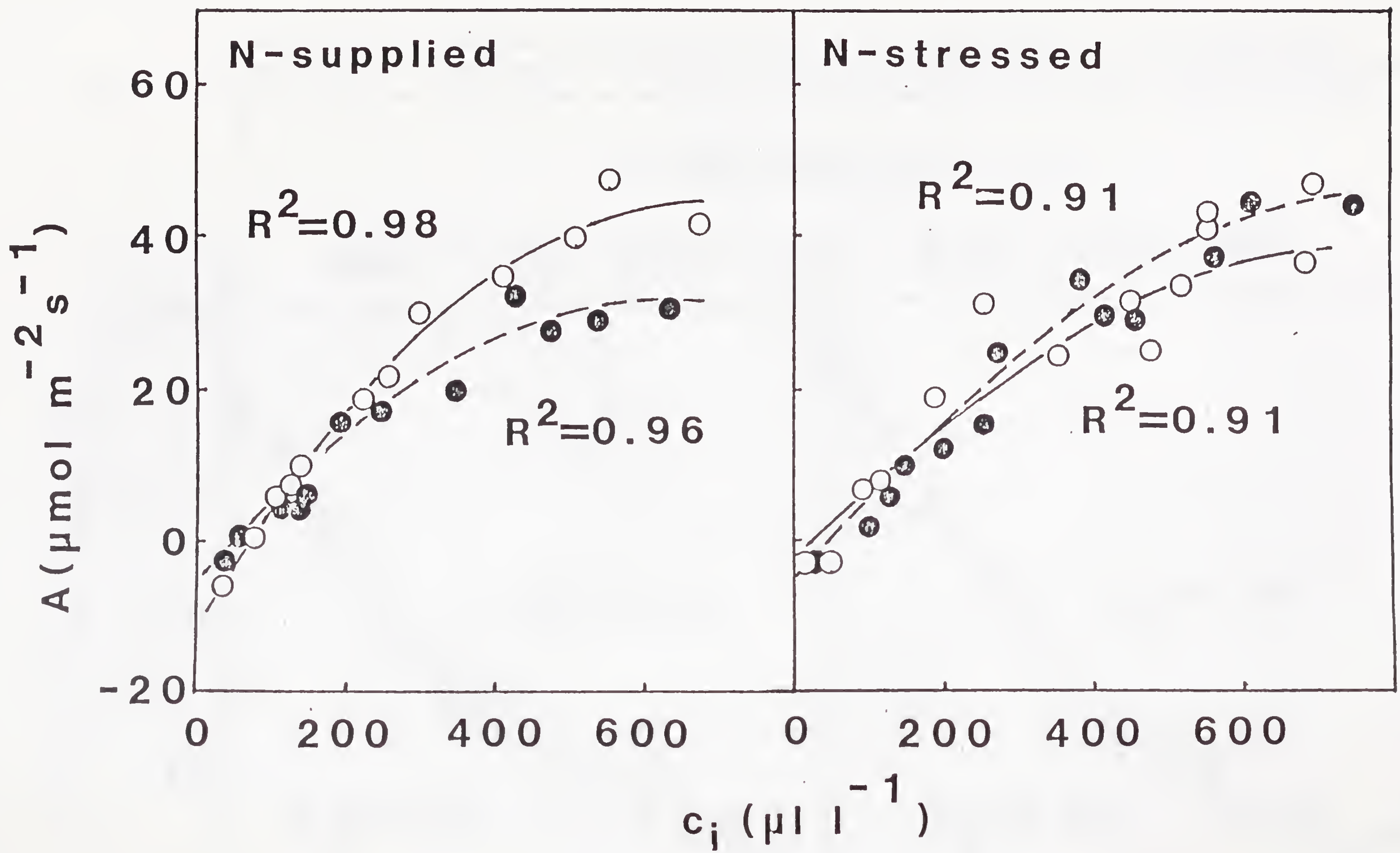

Figure 15. A(c_i) curves for plants grown at ambient CO_2 or enriched CO_2. Left panel: plots fertilized weekly with N. Right panel: no N added. All data shown are from the fully irrigated treatment. These curves are from data collected on JD 267. o – o, ambient CO_2; • – – •, enriched CO_2.

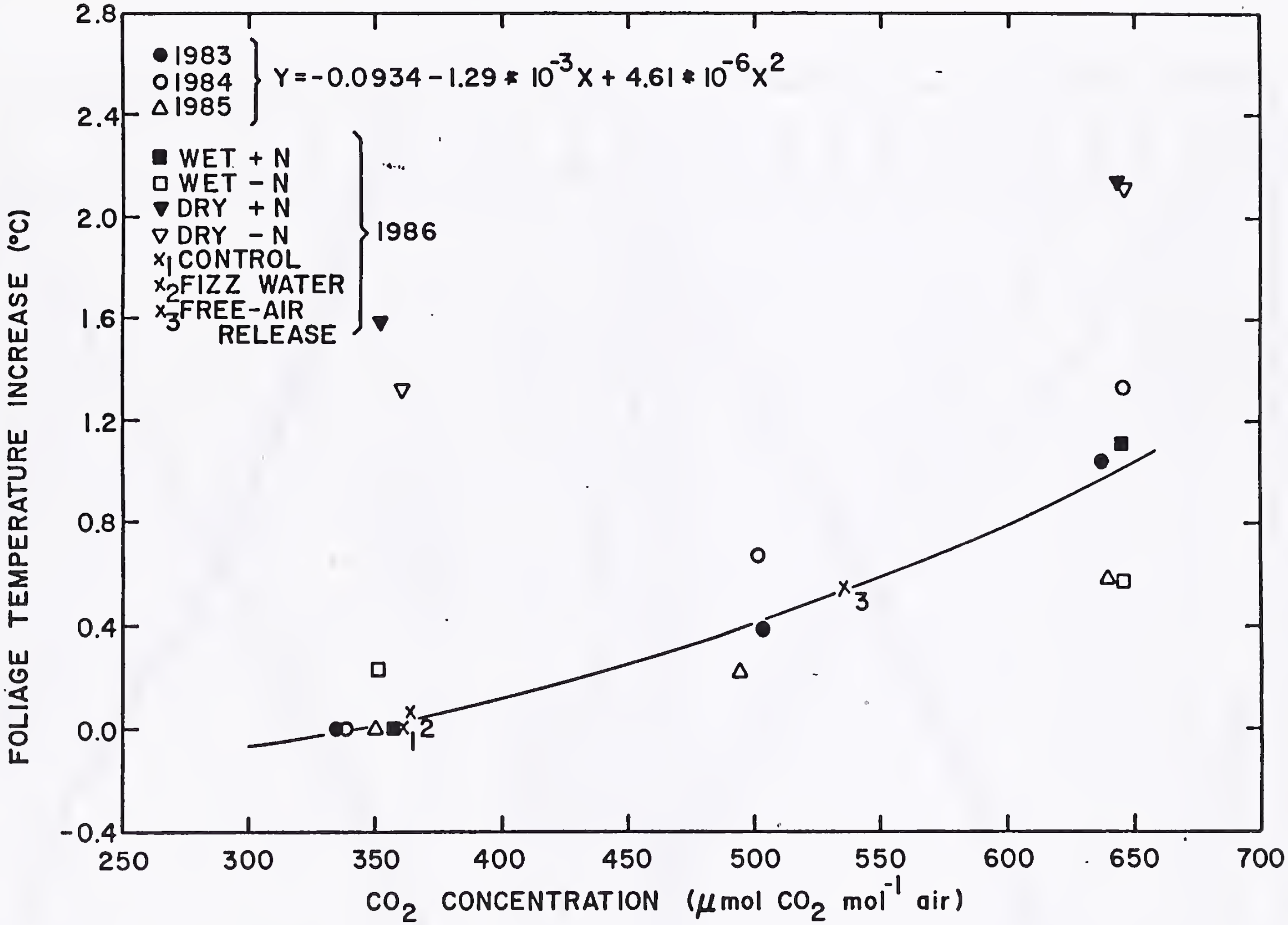

Figure 16. Cotton foliage temperature increase caused by atmospheric CO_2 enrichment. The curve is the regression fit to the data from 3 prior years (Kimball et al., 1985). The symbols are 1986 data from the CO_2/WATER/NITROGEN and FIZZ/FACE experiments, each point the average of 2 or 4 replicate plots, respectively.

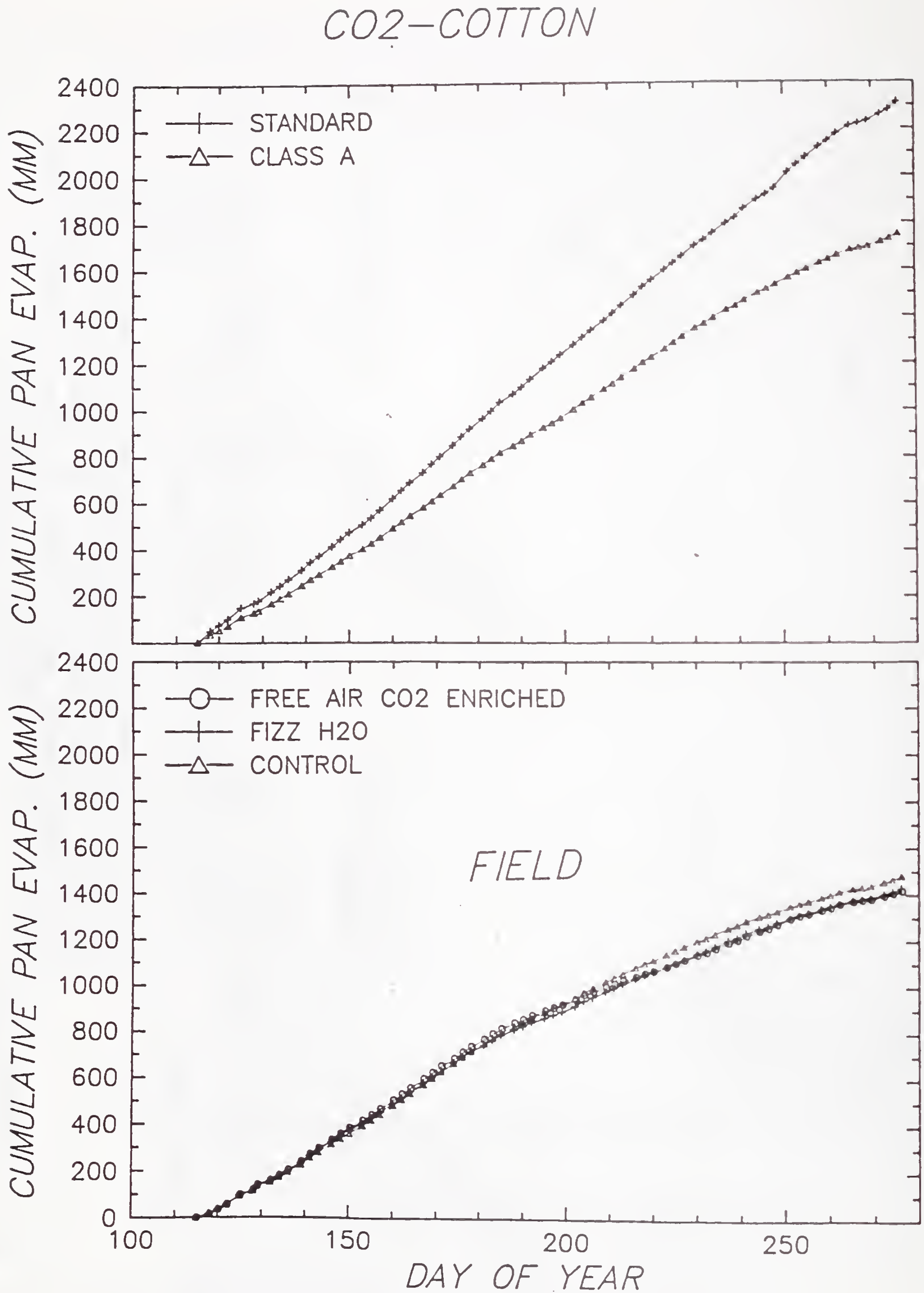

Figure 17. Cumulative pan evaporation through the 1986 growing season from a standard Class A pan over bare soil beside the cotton field and also from a small (250 mm-dia.) "standard" pan adjacent to the Class A pan (upper). Also the cumulative pan evaporation from small pans in replicate 1 of the control, FIZZ, and FACE (free-air CO_2-enriched) plots of the FIZZ/FACE experiment.

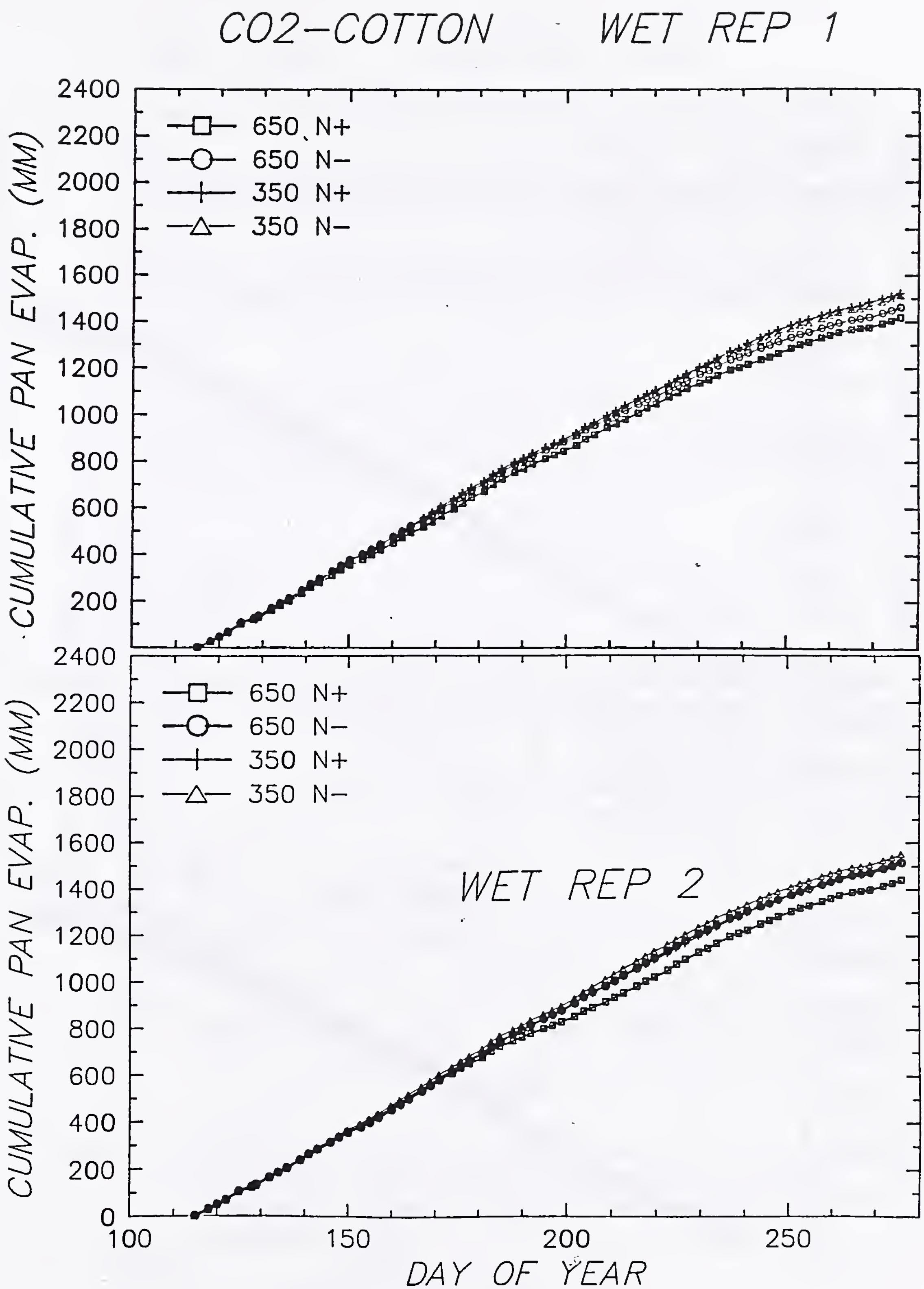

Figure 18. Cumulative pan evaporation through the 1986 growing season from small pans placed in the open-top chambers for the wet plots of the CO_2/WATER/NITROGEN experiment.

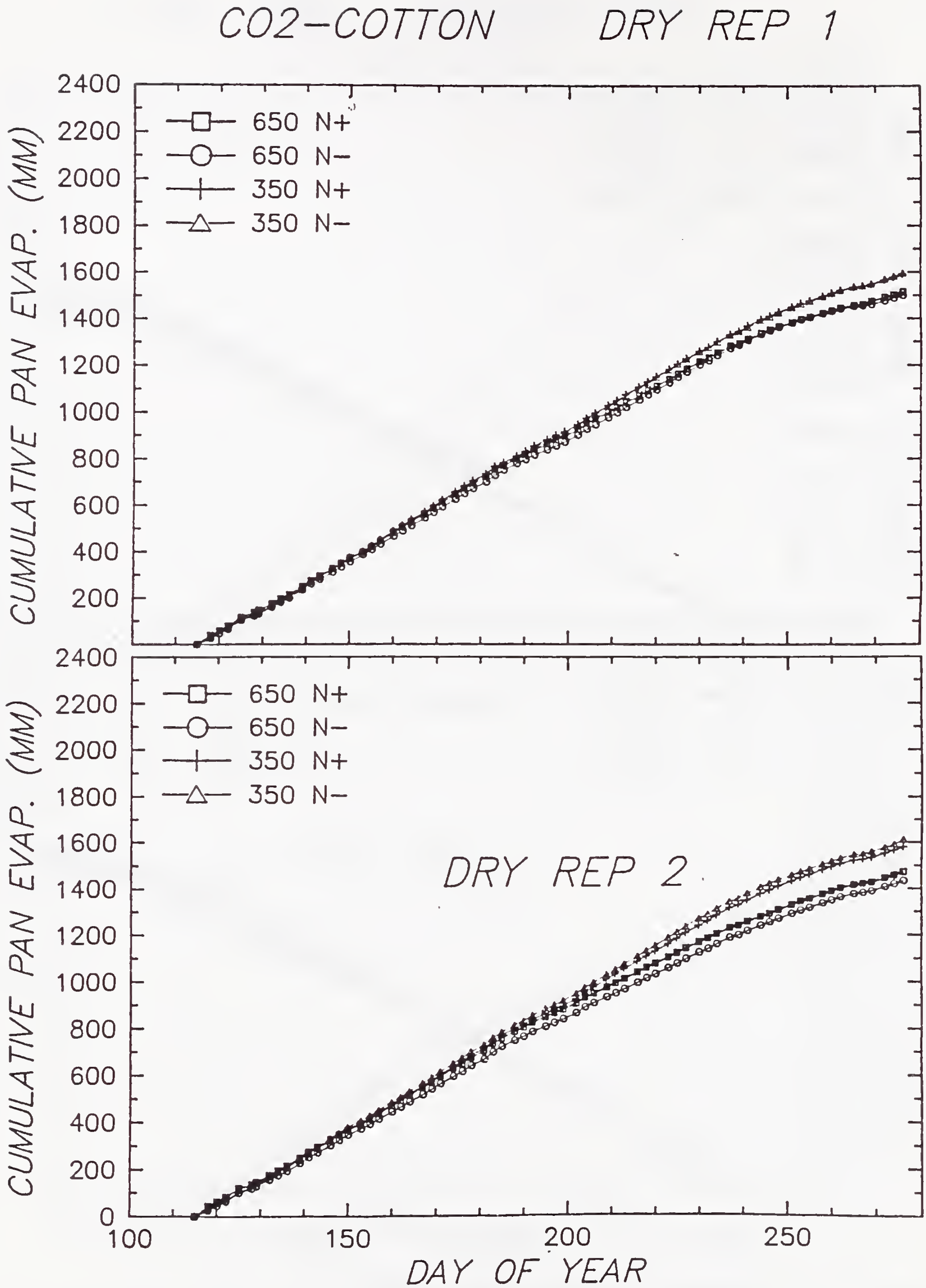

Figure 19. Cumulative pan evaporation through the 1986 growing season from small pans placed in the open-top chambers for the dry plots of the CO_2/WATER/NITROGEN experiment.

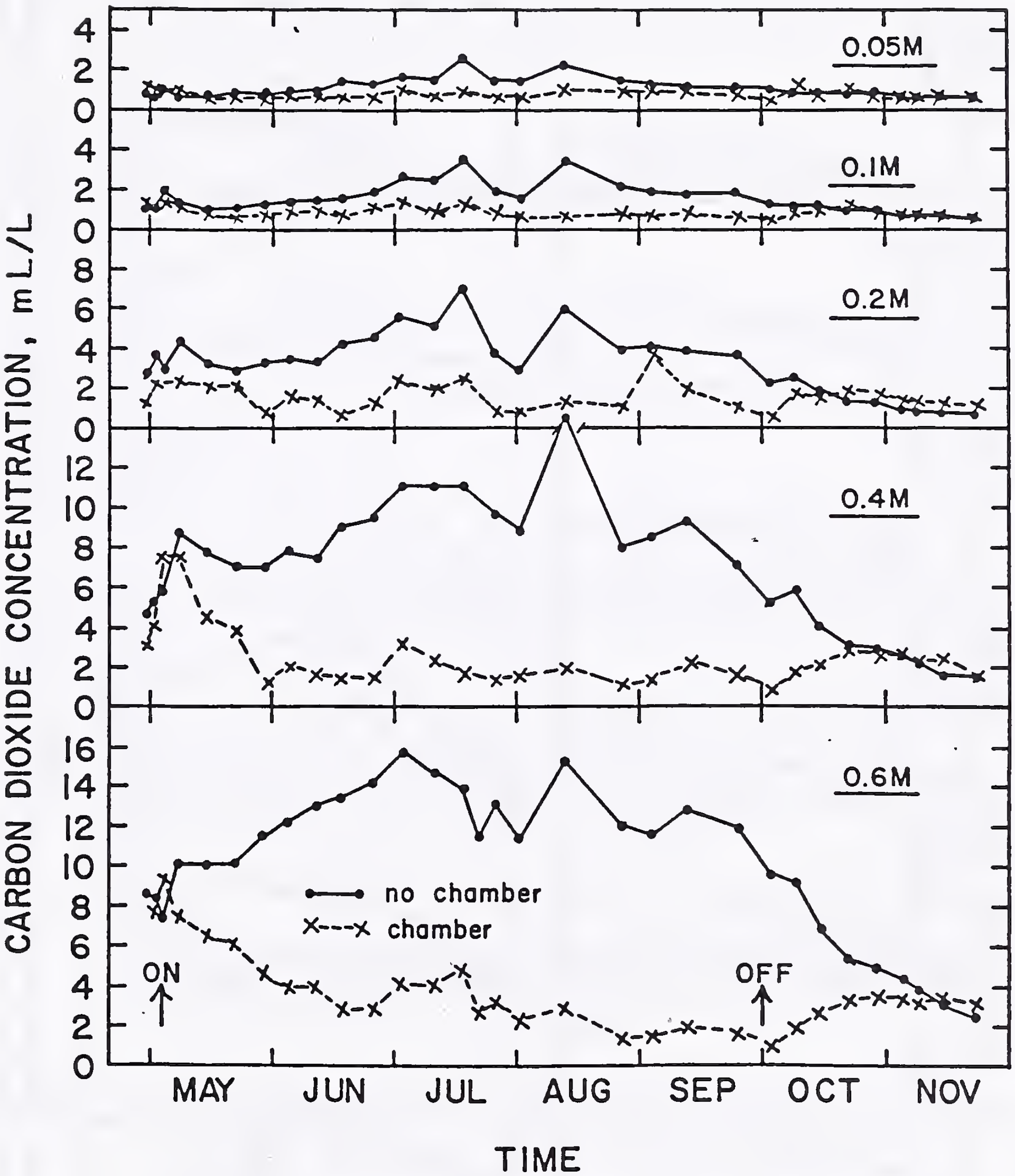

Figure 20. Soil carbon dioxide concentration in the soil profile at various times inside and outside the open-top chambers. (Blower started 02 May and stopped 02 October 1985).

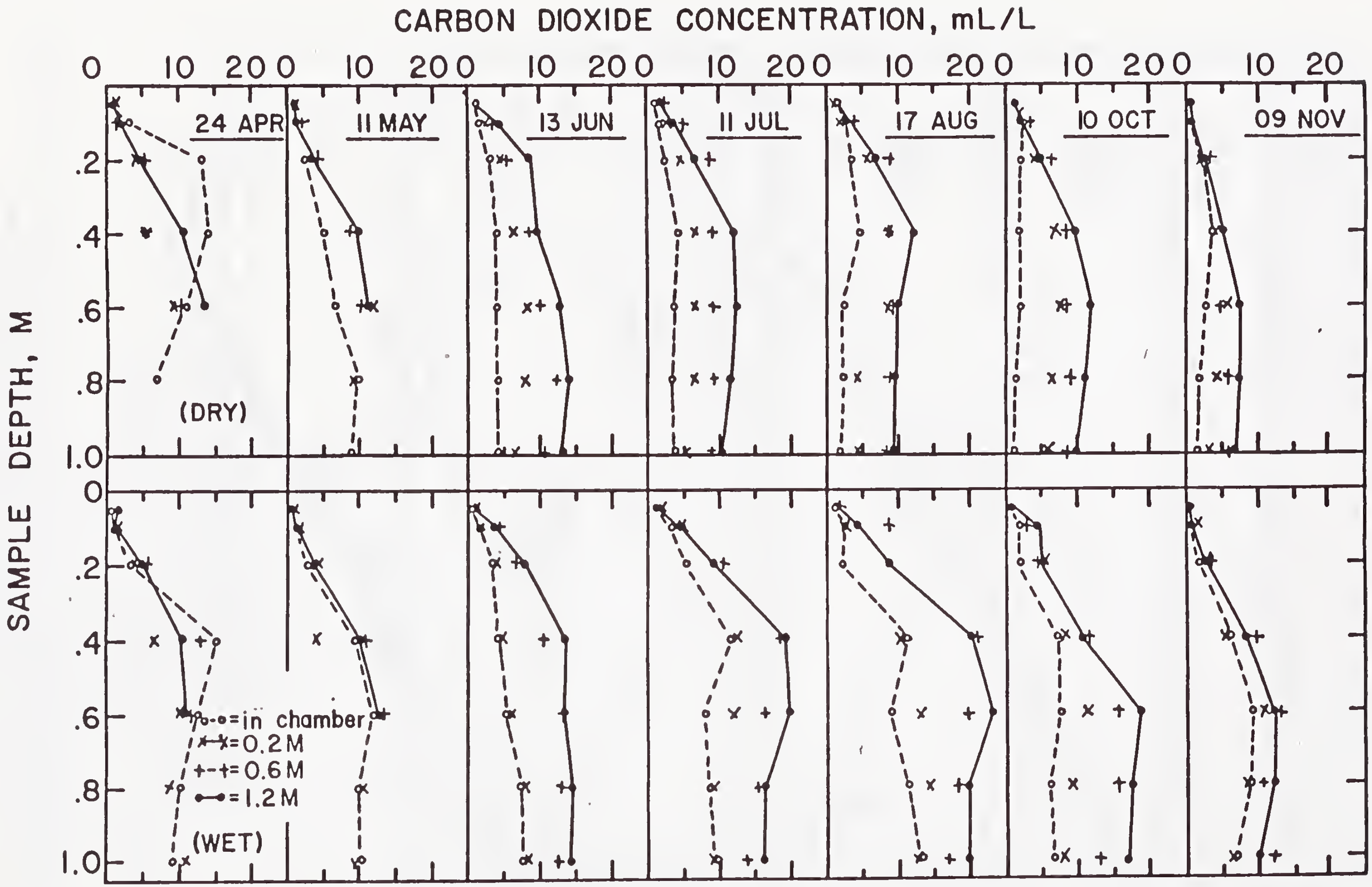

Figure 21. Soil carbon dioxide concentration profiles at the various depth X distance from chamber combinations during and after the cotton planting (Blower started 26 April and stopped 10 October 1986).

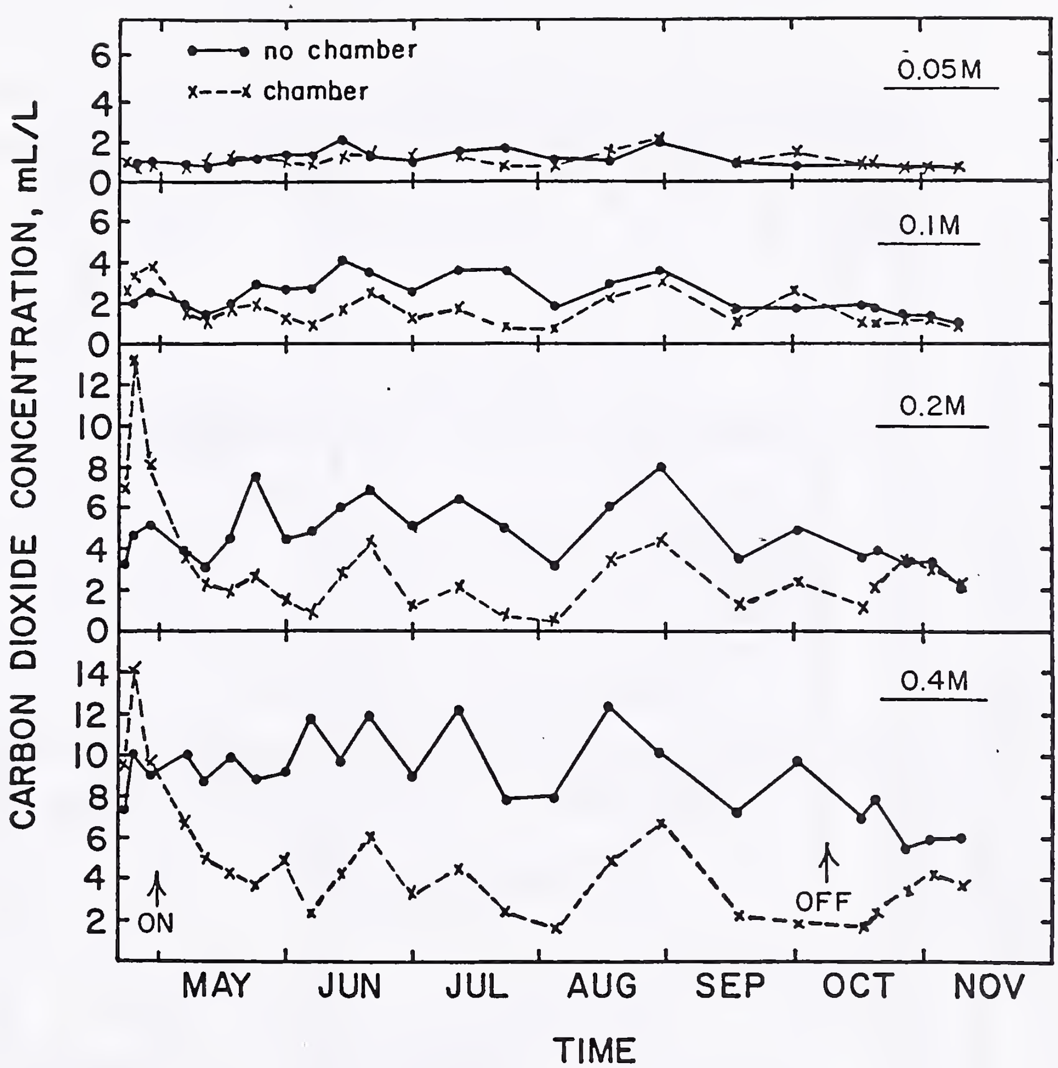

Figure 22. Soil carbon dioxide concentration at depths of 0.05, 0.1, 0.2 and 0.4 m inside and outside the open-top chamber versus time during the year for the CO_2-cotton 1986 experiment.

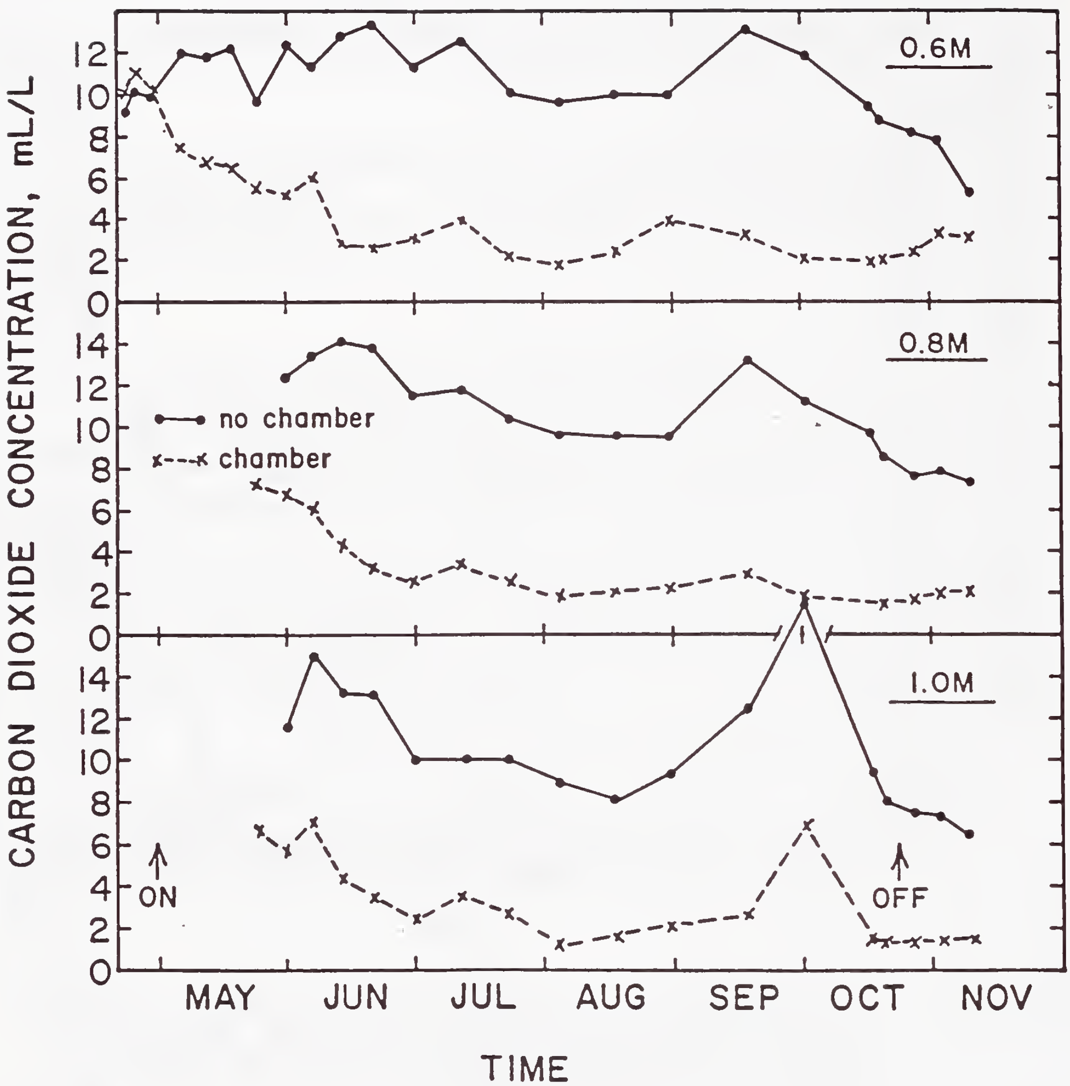

Figure 23. Soil carbon dioxide concentration at depths of 0.6, 0.8 and 1.0 m inside and outside the open-top chamber versus time during the year for the CO_2-cotton 1986 experiment.

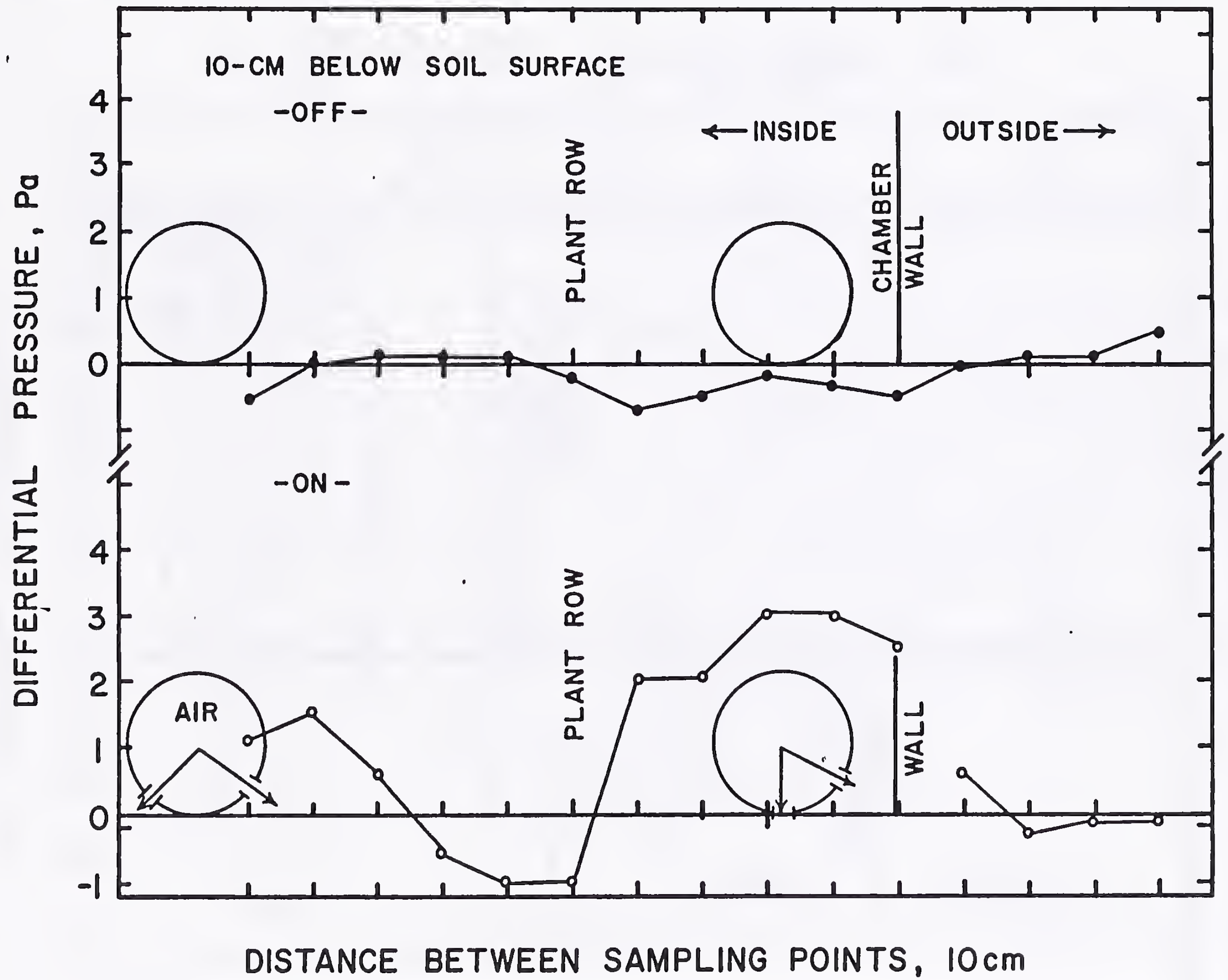

Figure 24. Differential pressures at the soil surface inside and outside the open-top chamber with the blower "off" and "on".

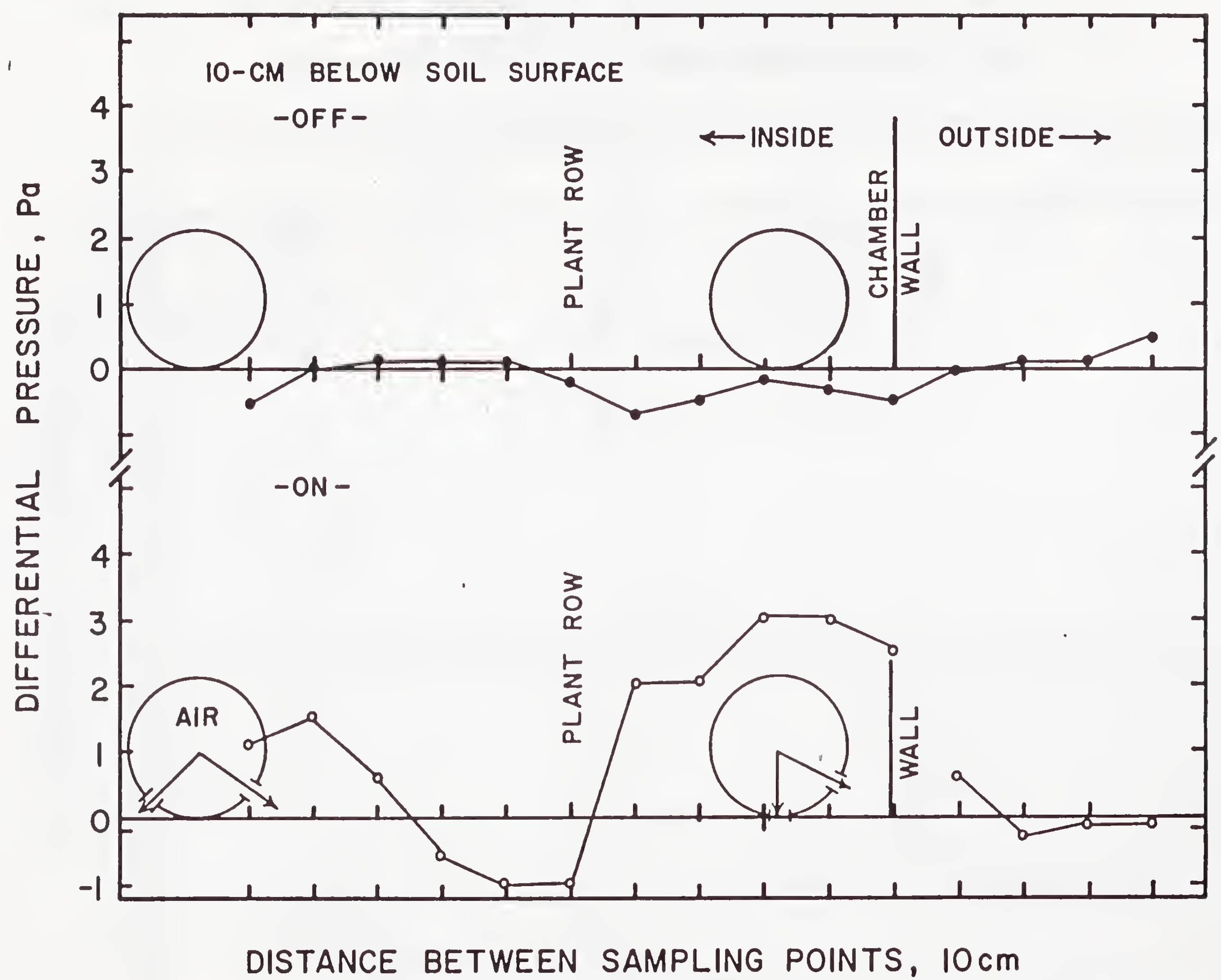

Figure 25. Differential pressure 0.1 m below the soil surface inside and outside the open-top chamber with the blower "off" and "on".

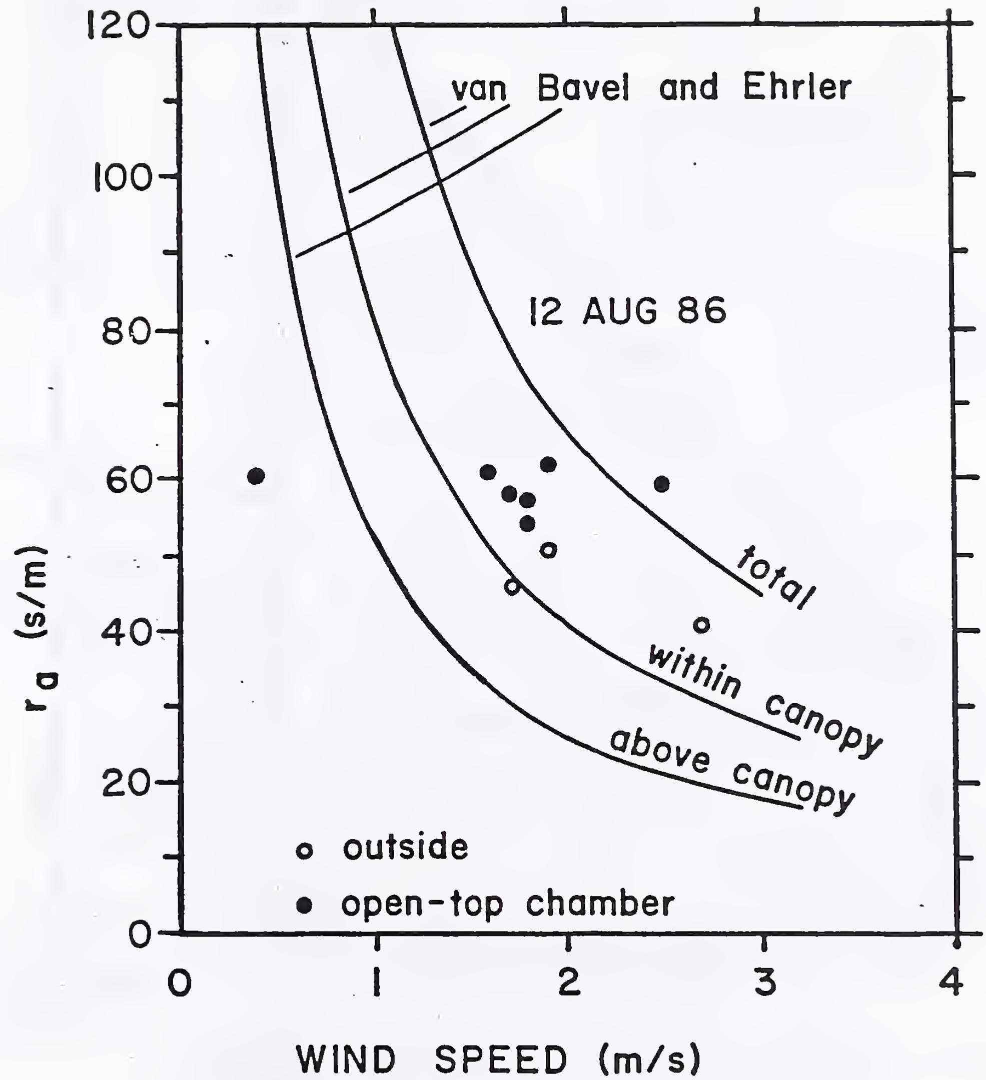

Figure 26. Aerodynamic resistance, r_a, determined using a blotter paper cotton "plant" on 12 August 1986 plotted as a function of wind speed. The curves are empirical relationships from van Bavel and Ehrler (1968) for the aerodynamic resistance above and within a sorghum canopy.

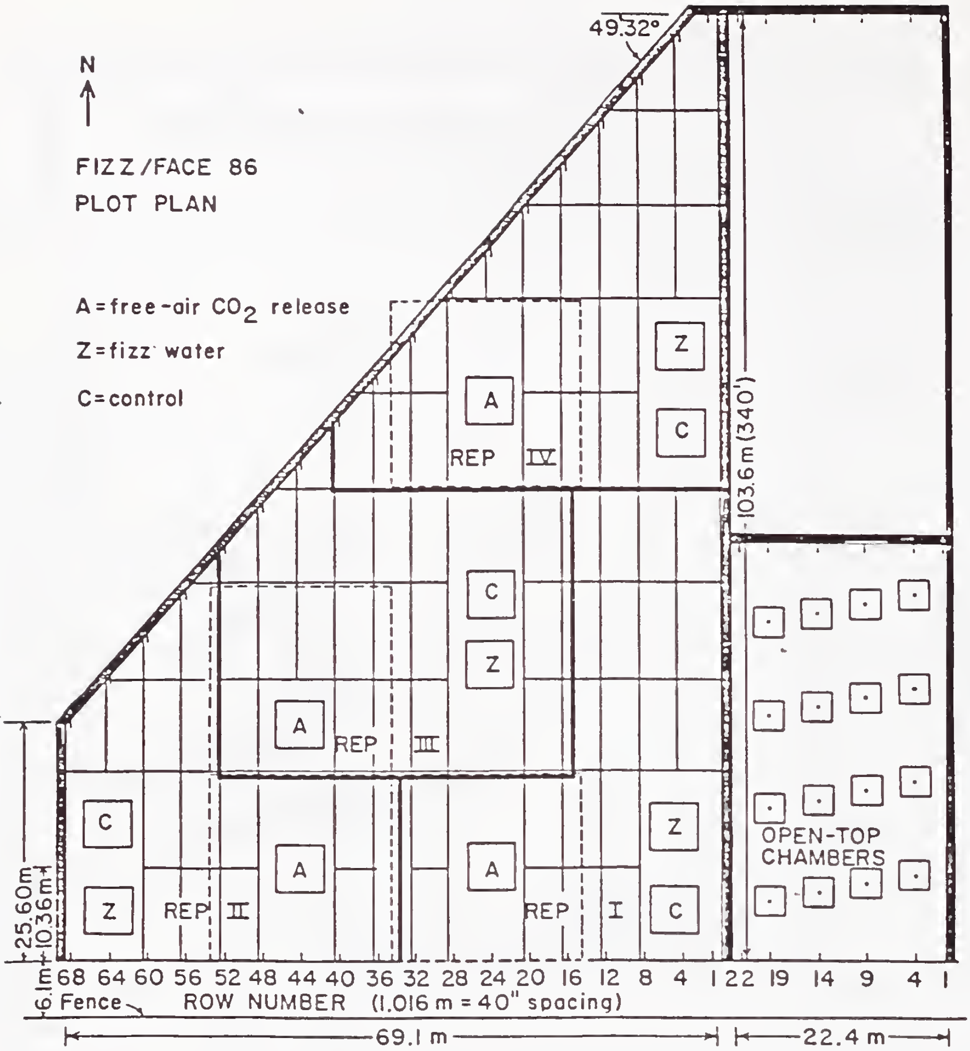

Figure 27. Plot plan for the 1986 FIZZ/FACE experiment showing the plot arrangement on the field and the relative location of the open-top chambers for the CO_2/WATER/NITROGEN experiment. The medium heavy lines demarcate the separate 4 replicates which were irrigated individually, except for the FIZZ plot areas which were all irrigated together. The small rectangular plots demarcated by fine solid lines were for an independent cotton breeding experiment. The dashed lines demarcate the 20 m borders of the CO_2-enriched area for each of the FACE (A) plots.

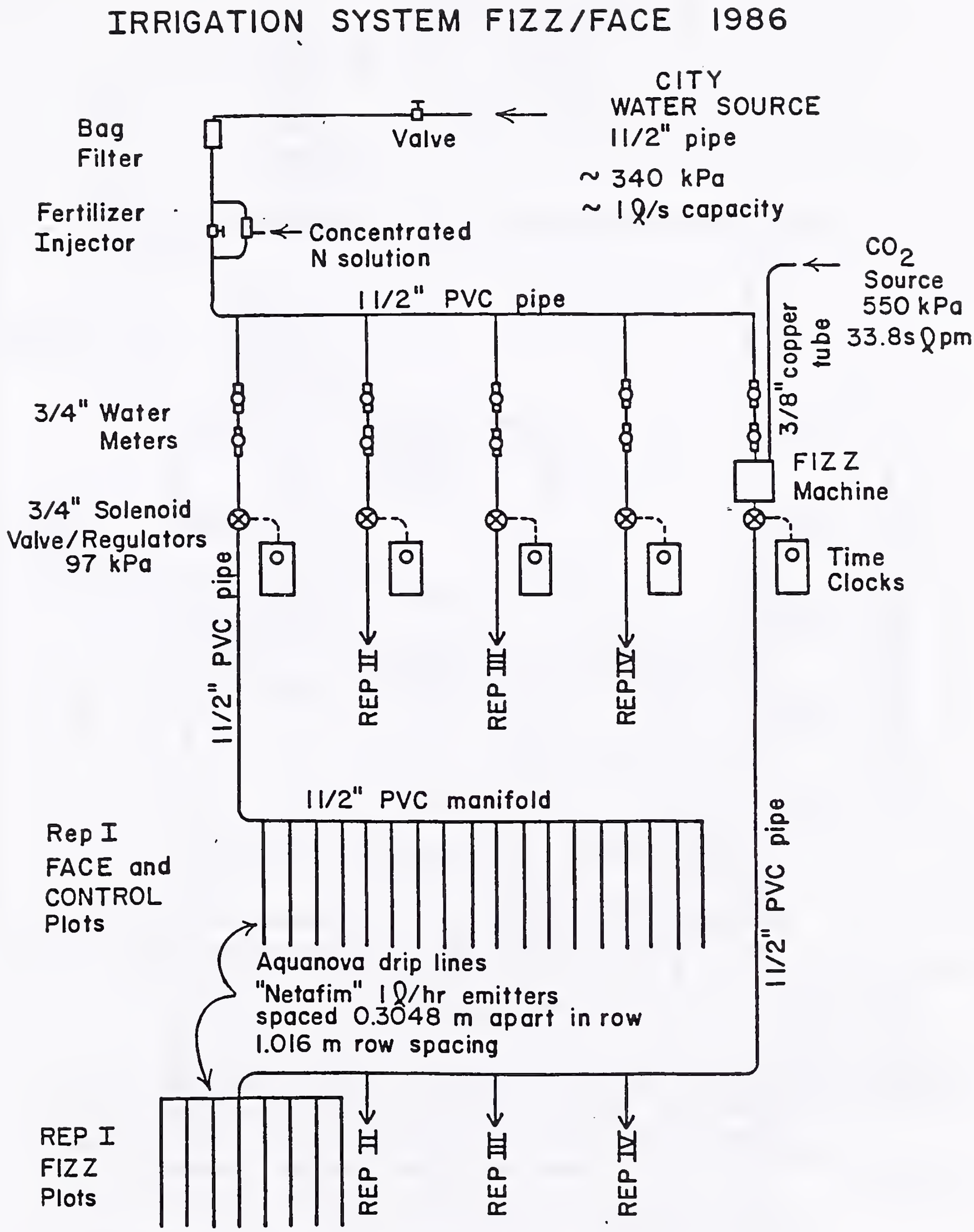

Figure 28. Schematic diagram of the irrigation system for the FIZZ/FACE experiment, also showing the carbonator (FIZZ machine) for supersaturating the FIZZ plot irrigation water with CO_2.

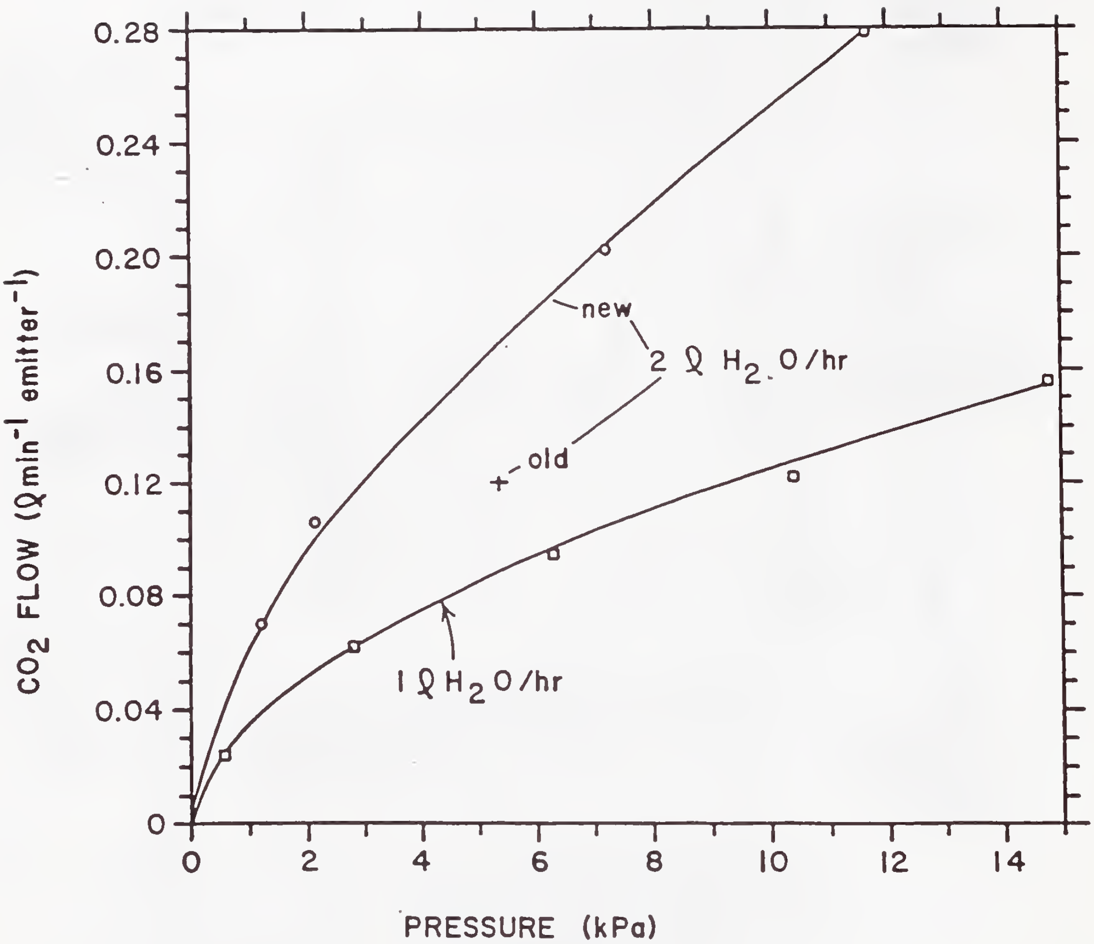

Figure 29. Gaseous CO_2 delivery curves versus pressure drop for Aquanova "Netafim" drip irrigation emitters normally used to deliver 1 or 2 ℓ/hr of water. The + denotes one point determined for an old (in irrigation service for 1 season) emitter, whereas the rest are for new emitters.

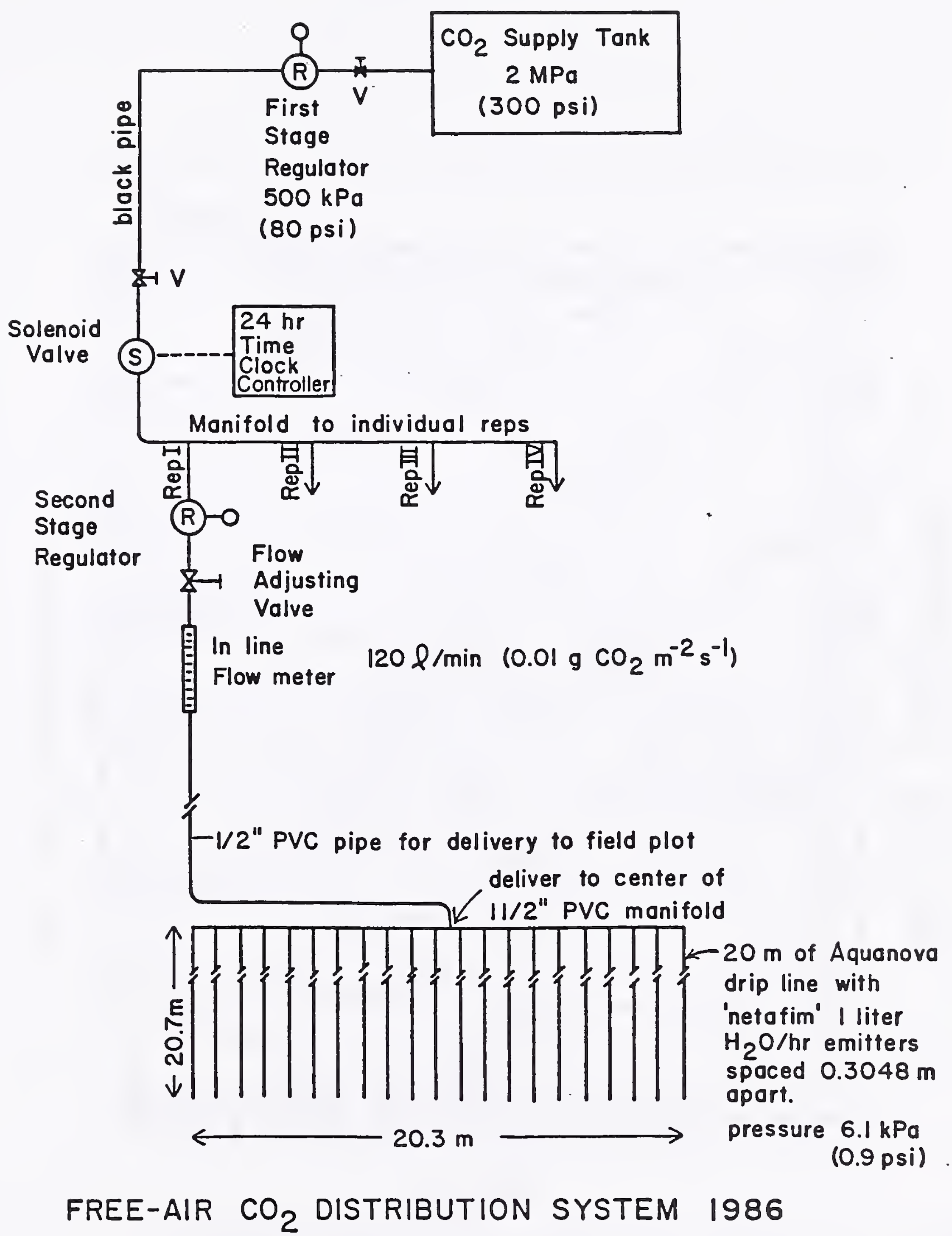

Figure 30. Schematic diagram of the CO_2 distribution system to the free-air CO_2 enrichment (FACE) plots.

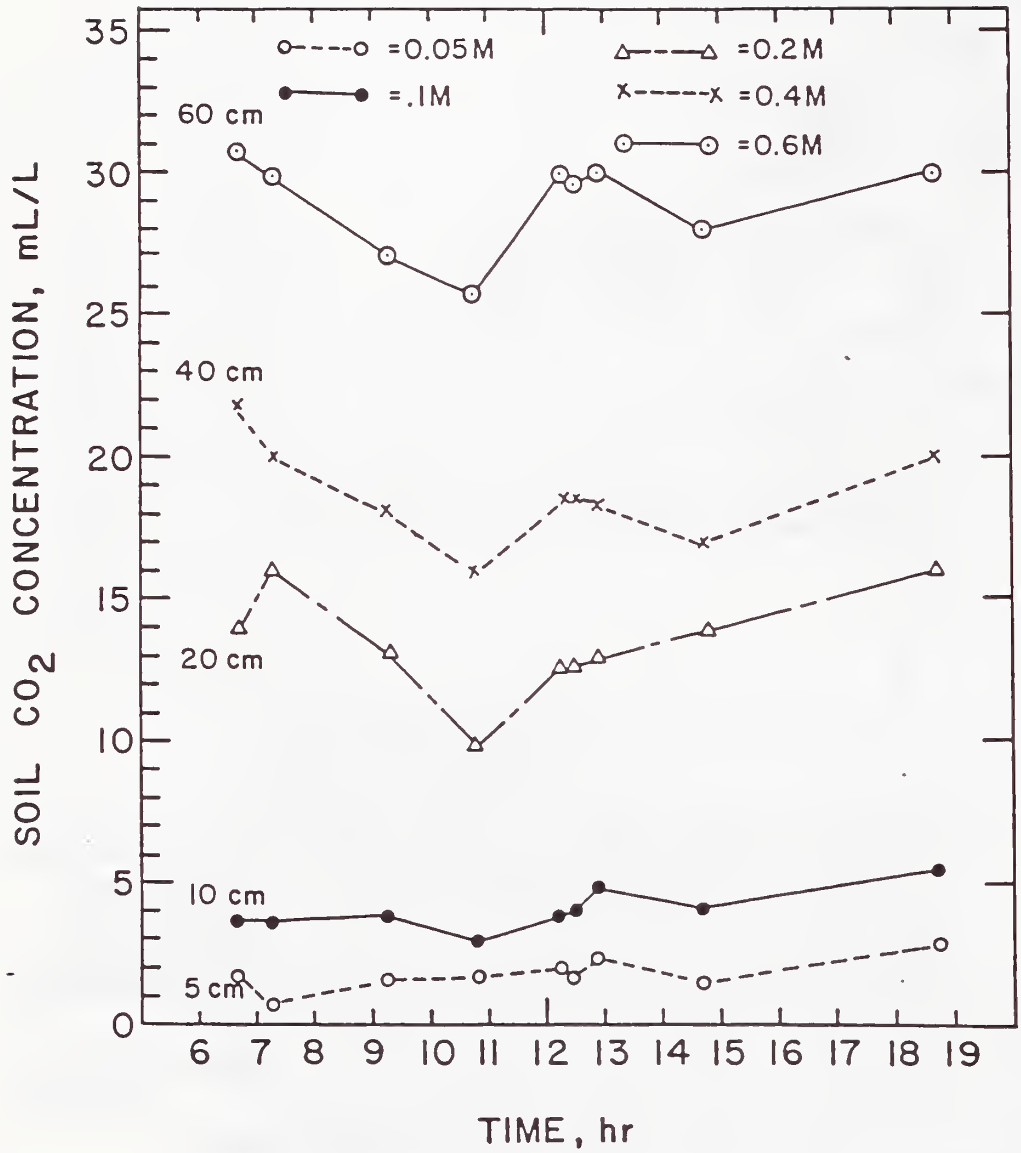

Figure 31. Soil CO_2 concentration at the various depths and times in the control plots irrigated using untreated water.

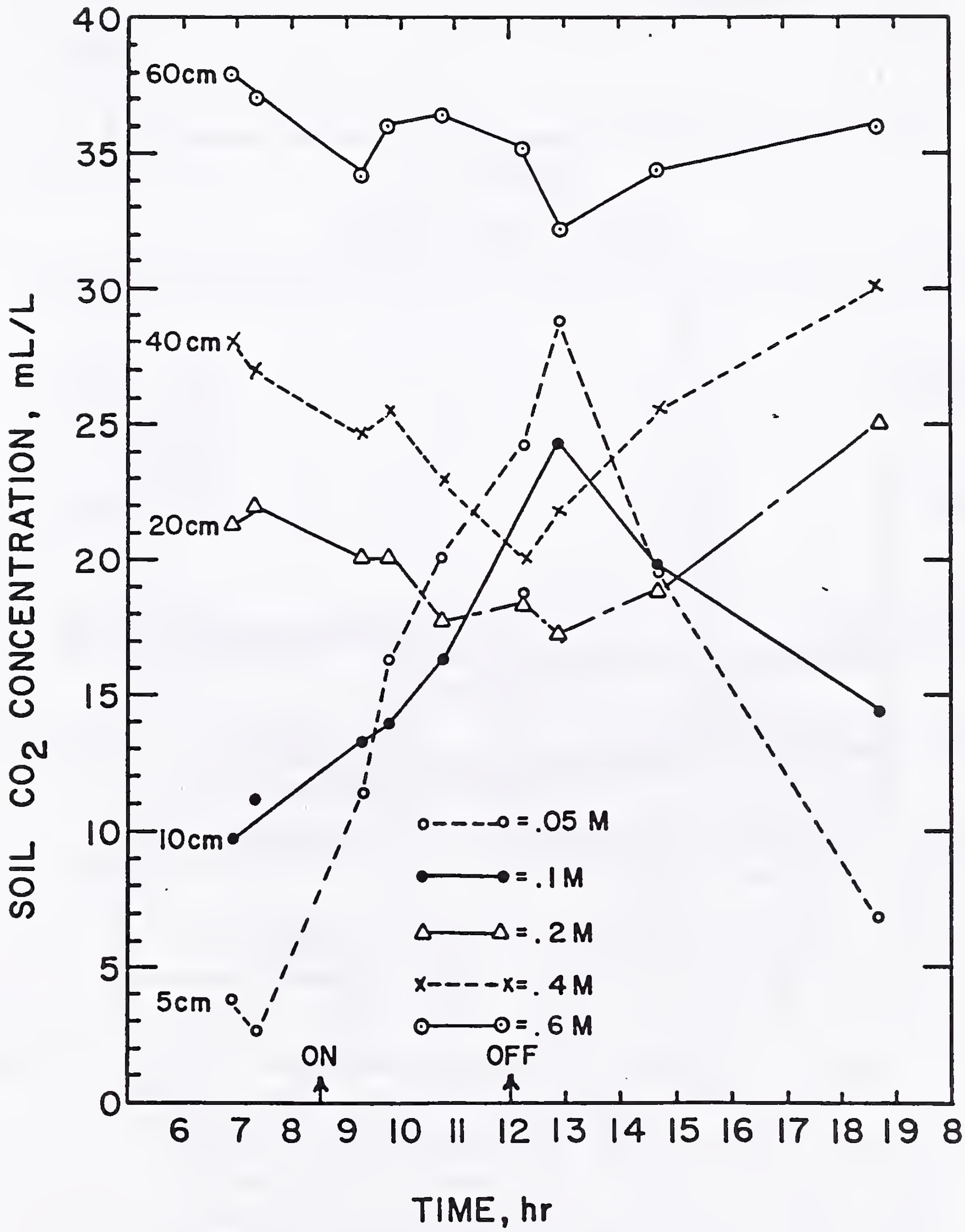

Figure 32. Soil CO_2 concentration at the various depths and times in the FIZZ plots irrigated using carbonated water.

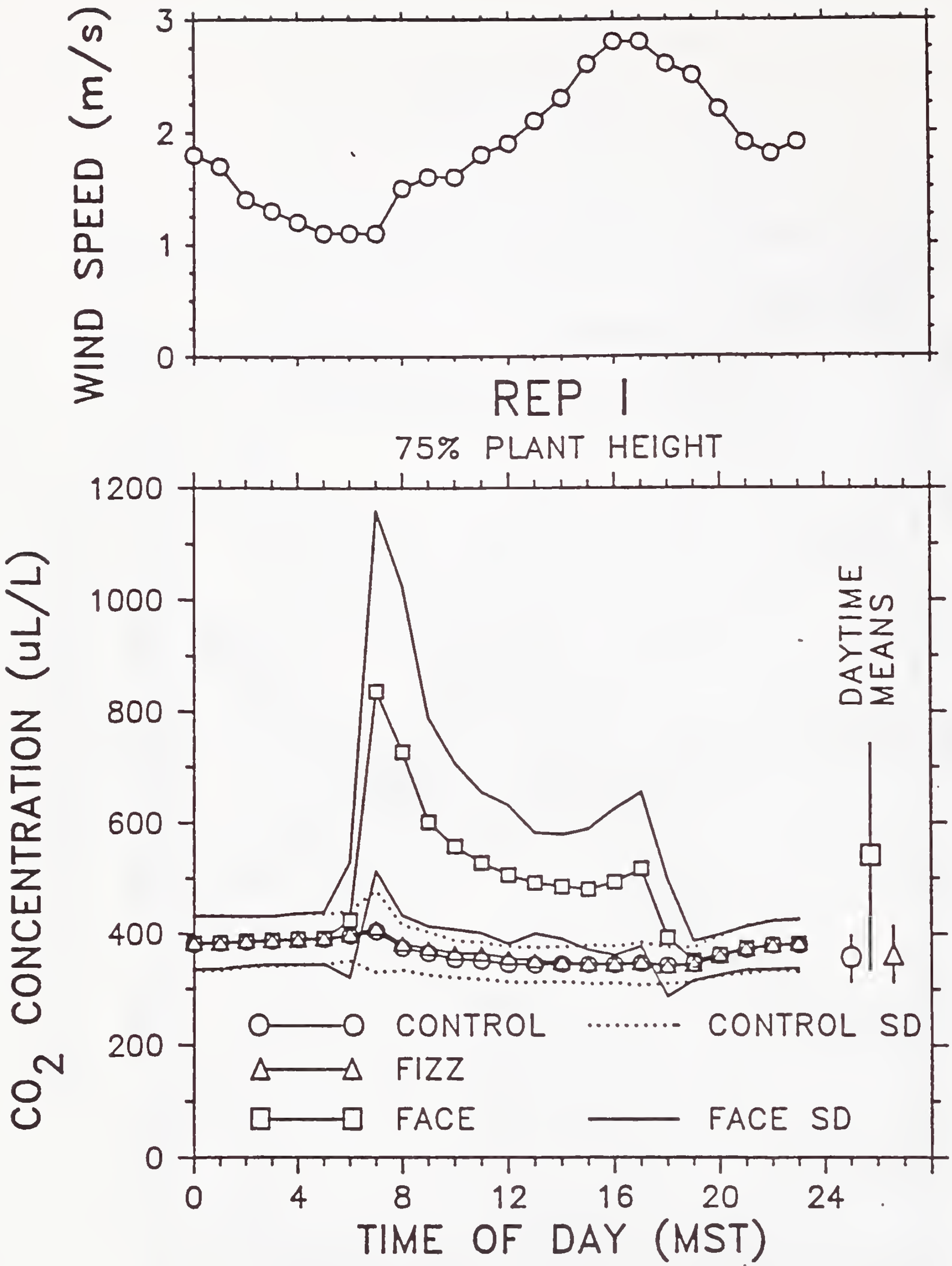

Figure 33. Diurnal course of mean CO_2 concentration averaged from 21 June through 28 September 1986 at the 75% plant height in rep 1 of the control, FIZZ, and FACE plots. Also shown are the standard deviation of the individual observations for the control and FACE plots and in the upper graph is the similarly averaged wind speed at the 2.5 m height on the weather mast.

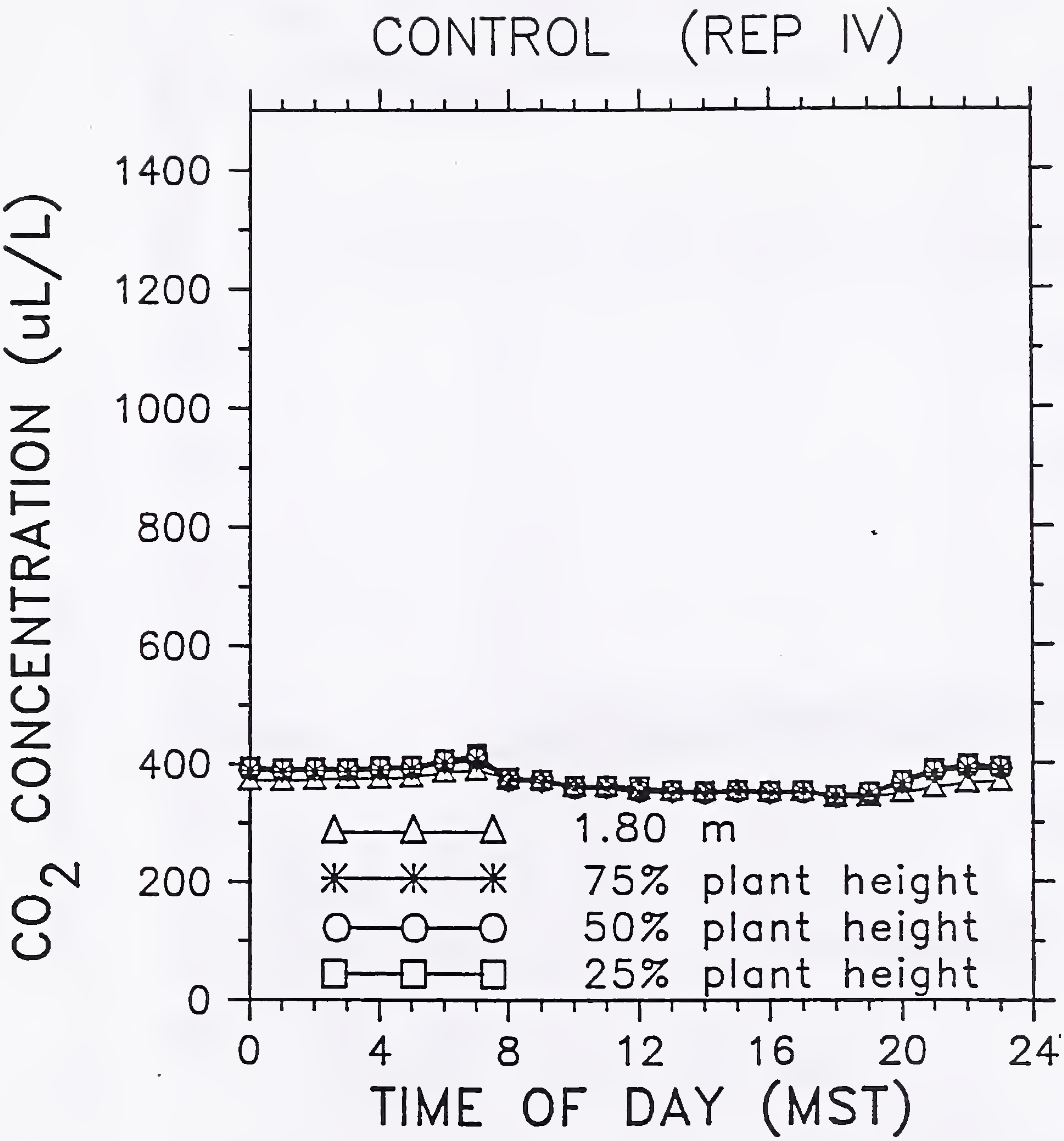

Figure 34. Diurnal course of mean CO_2 concentration averaged from 21 June through 28 September 1986 at various heights in the rep 4 control plots.

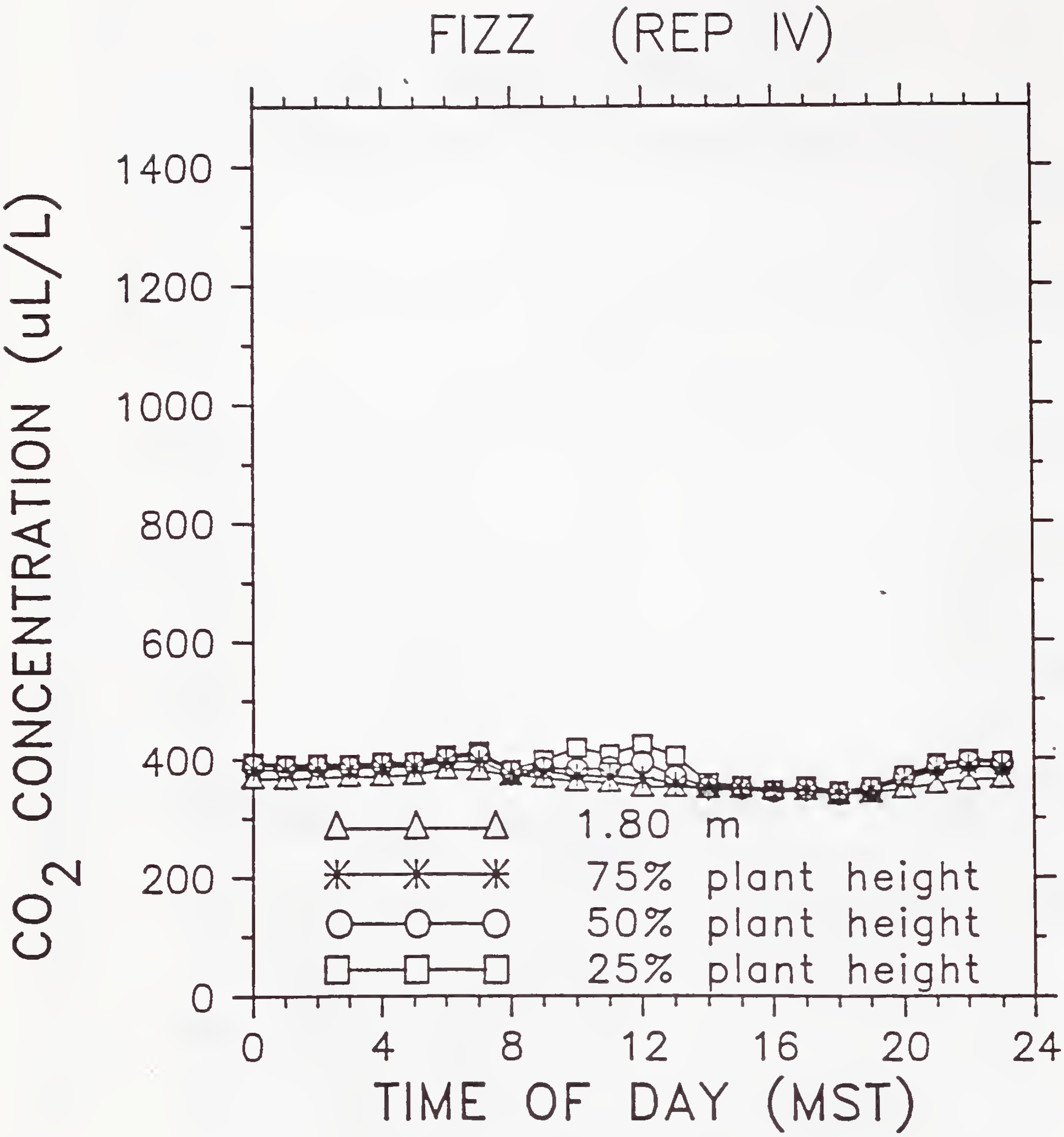

Figure 35. Diurnal course of mean CO_2 concentration averaged from 21 June through 28 September 1986 at various heights in the rep 4 FIZZ plots.

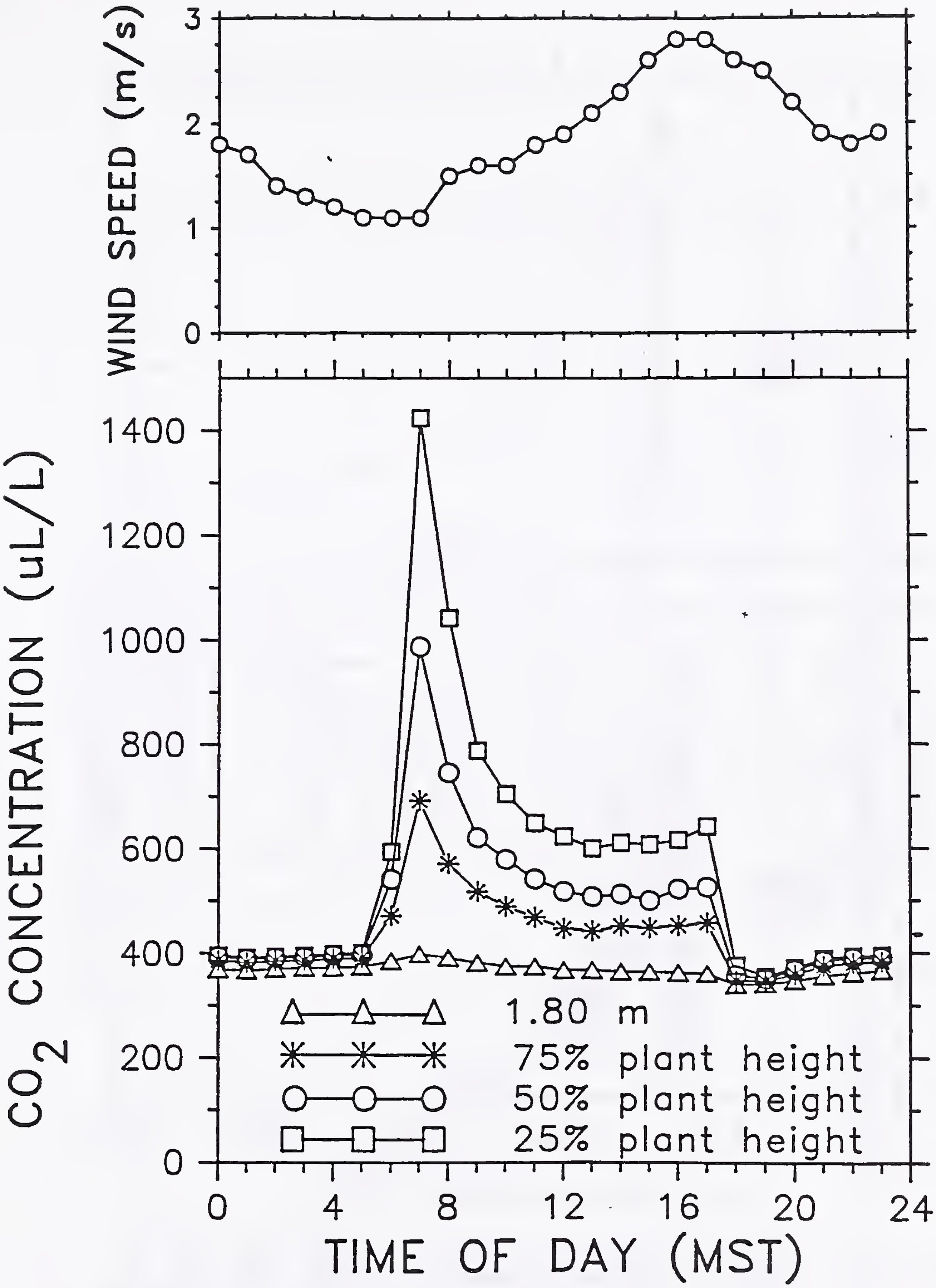

Figure 36. Diurnal course of mean CO_2 concentration averaged from 21 June through 28 September 1986 at various heights in the rep 4 FACE plots. Also shown in the upper part is the similarly averaged wind speed from the 2.5 m height at the weather mast.

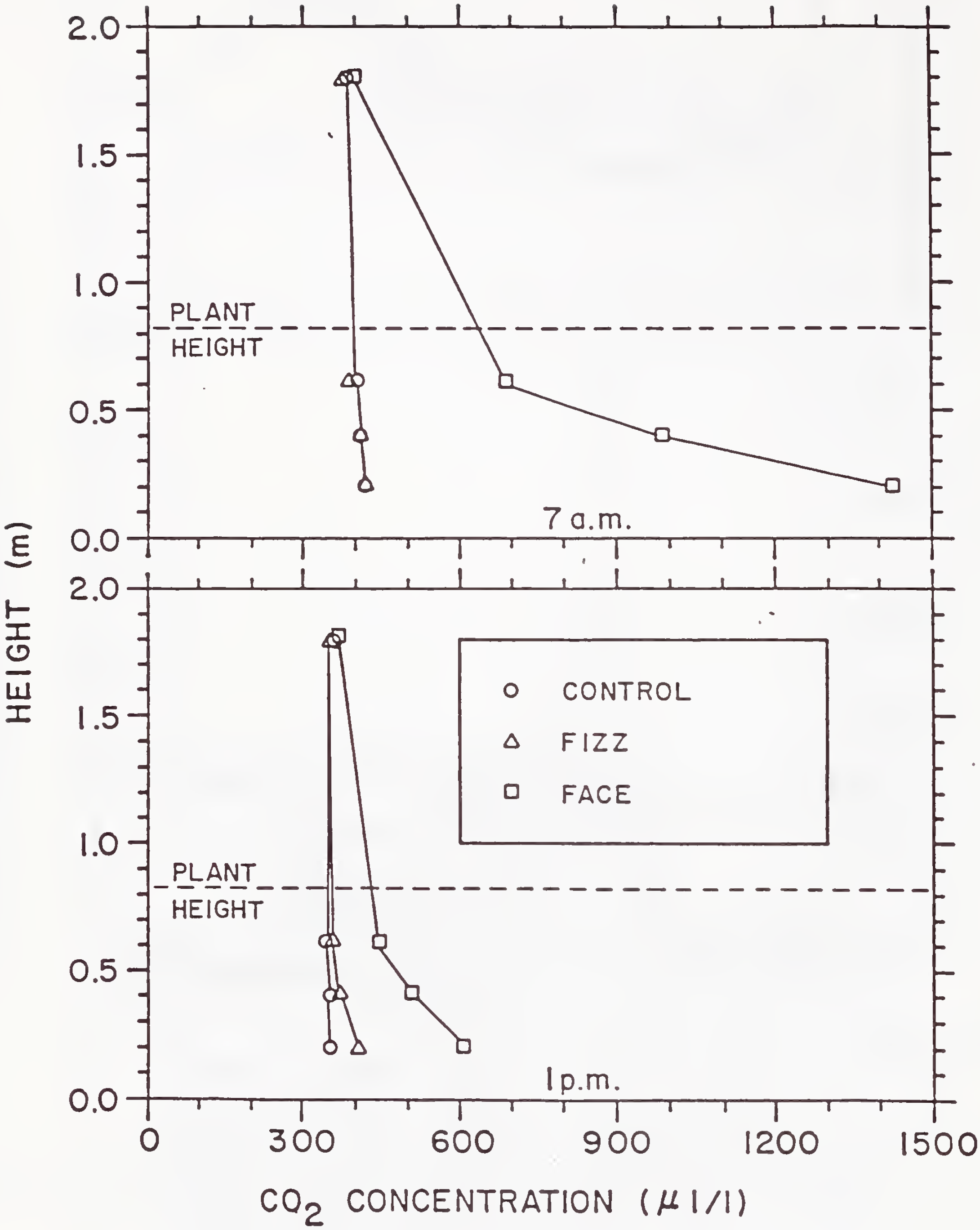

Figure 37. Vertical profiles of mean CO_2 concentration sampled during the hours ending at 7 am and at 1 pm for rep 4 of the control, FIZZ, and FACE plots in 1986.

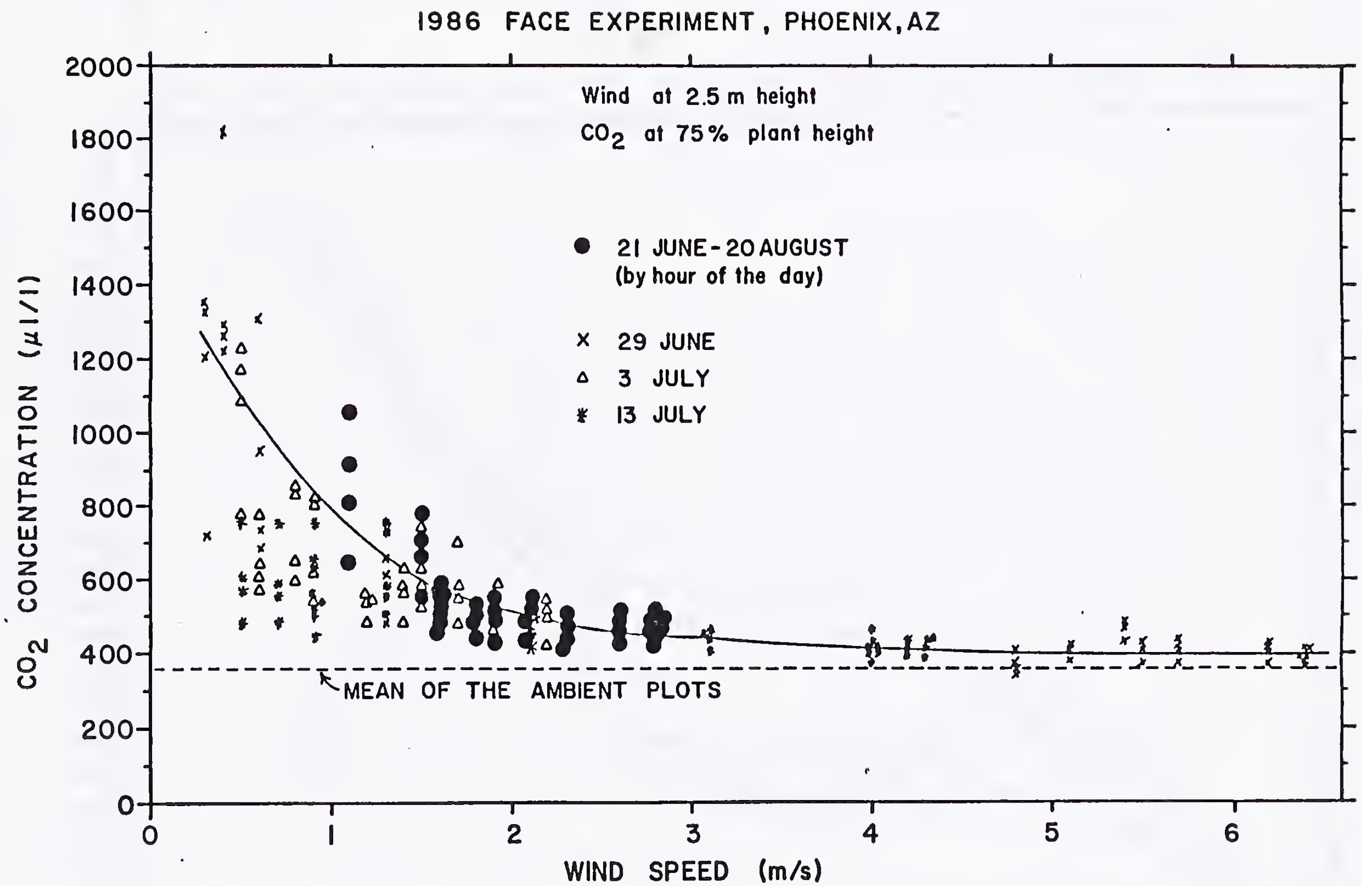

Figure 38. Mean hourly CO_2 concentrations at the 75% plant heights from selected days plotted against the corresponding mean hourly wind speeds.

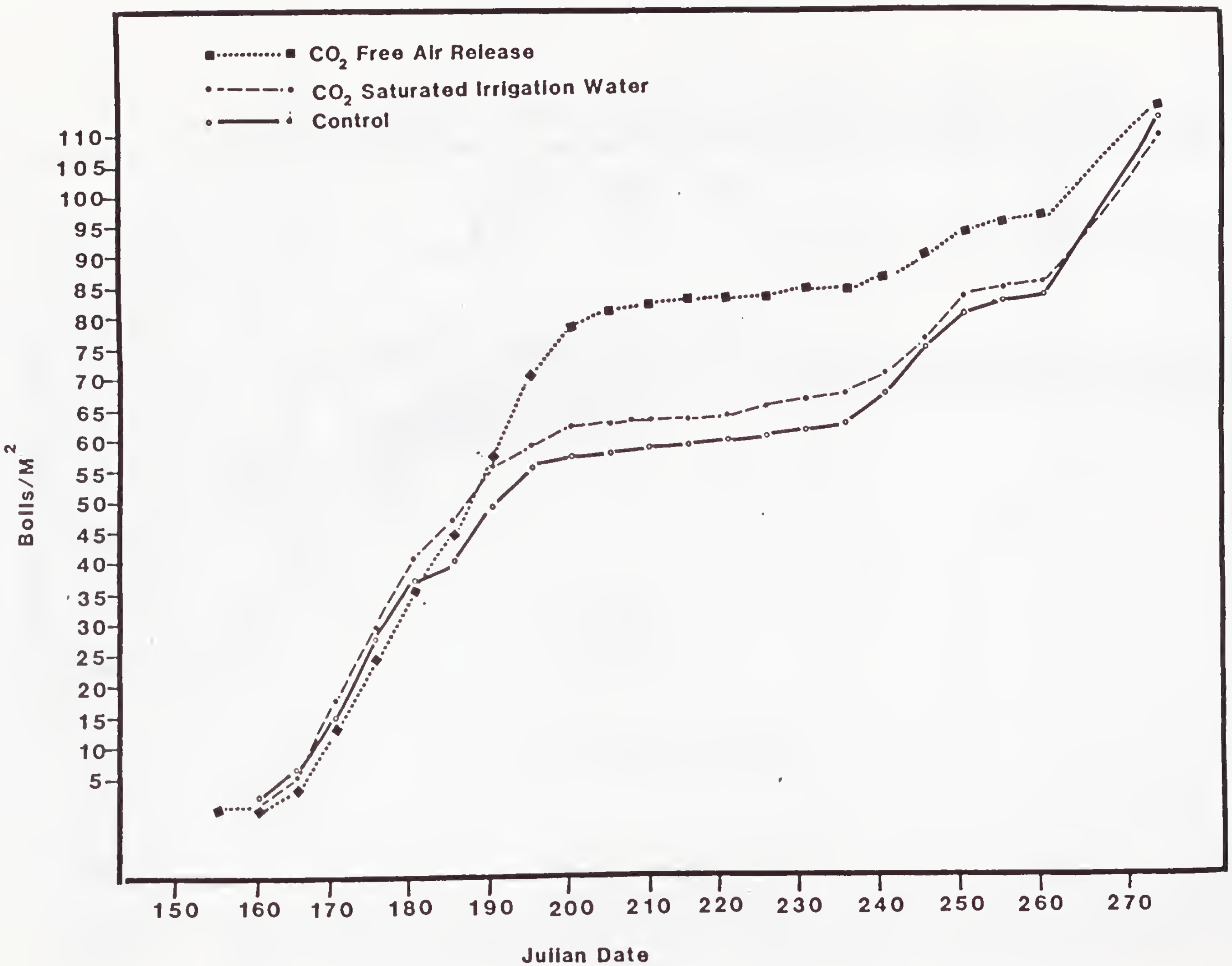

Figure 39. Accumulated boll load through the season in the FIZZ/FACE experiment. The data are weekly averages of the four replicates.

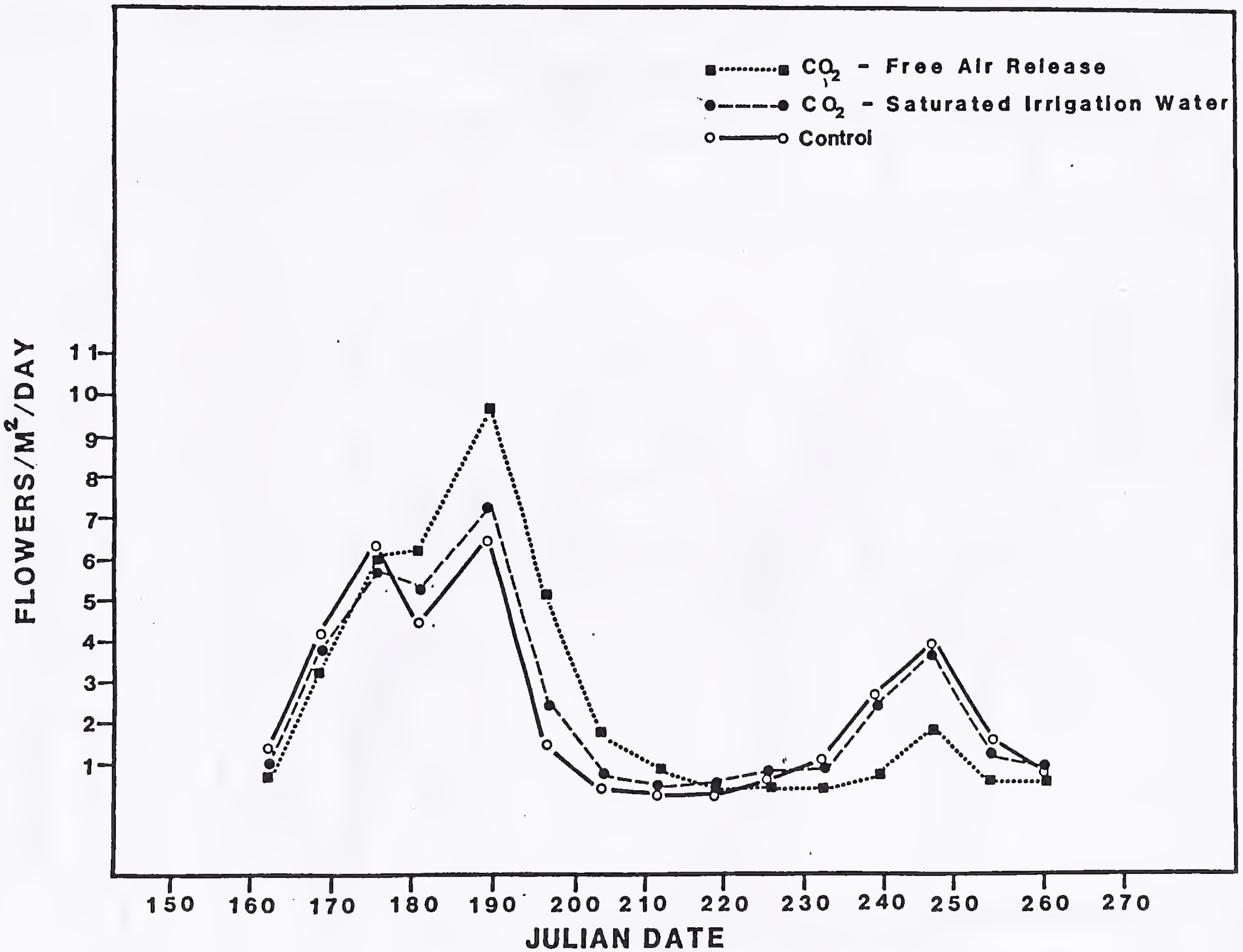

Figure 40. Rate of flower production in the FIZZ/FACE experiment. The data are weekly averages of four replications.

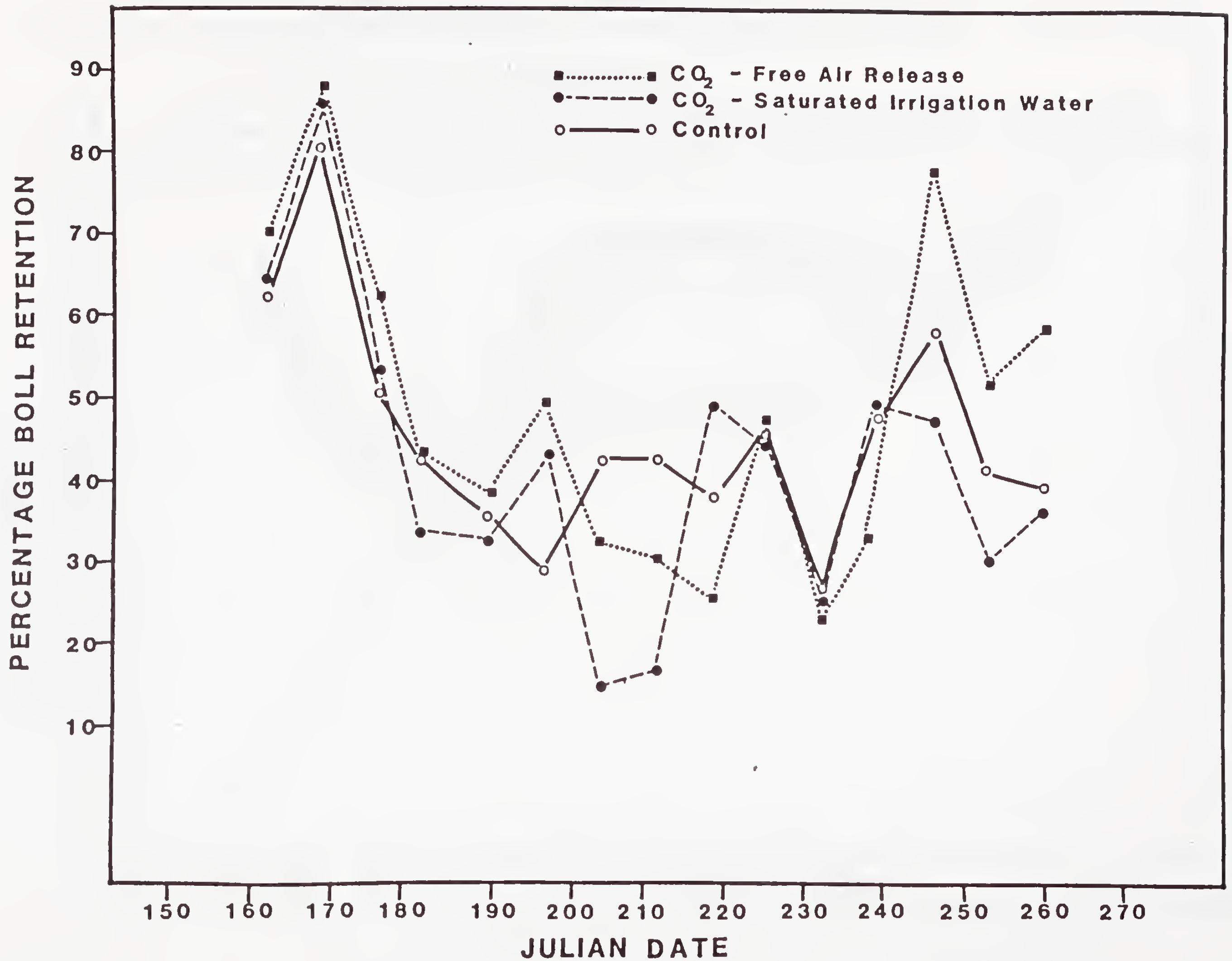

Figure 41. Boll retention in the FIZZ/FACE experiment. The data are the percentages of the weekly (and over 4 replications) averages of blossoms produced which resulted in harvestable bolls.

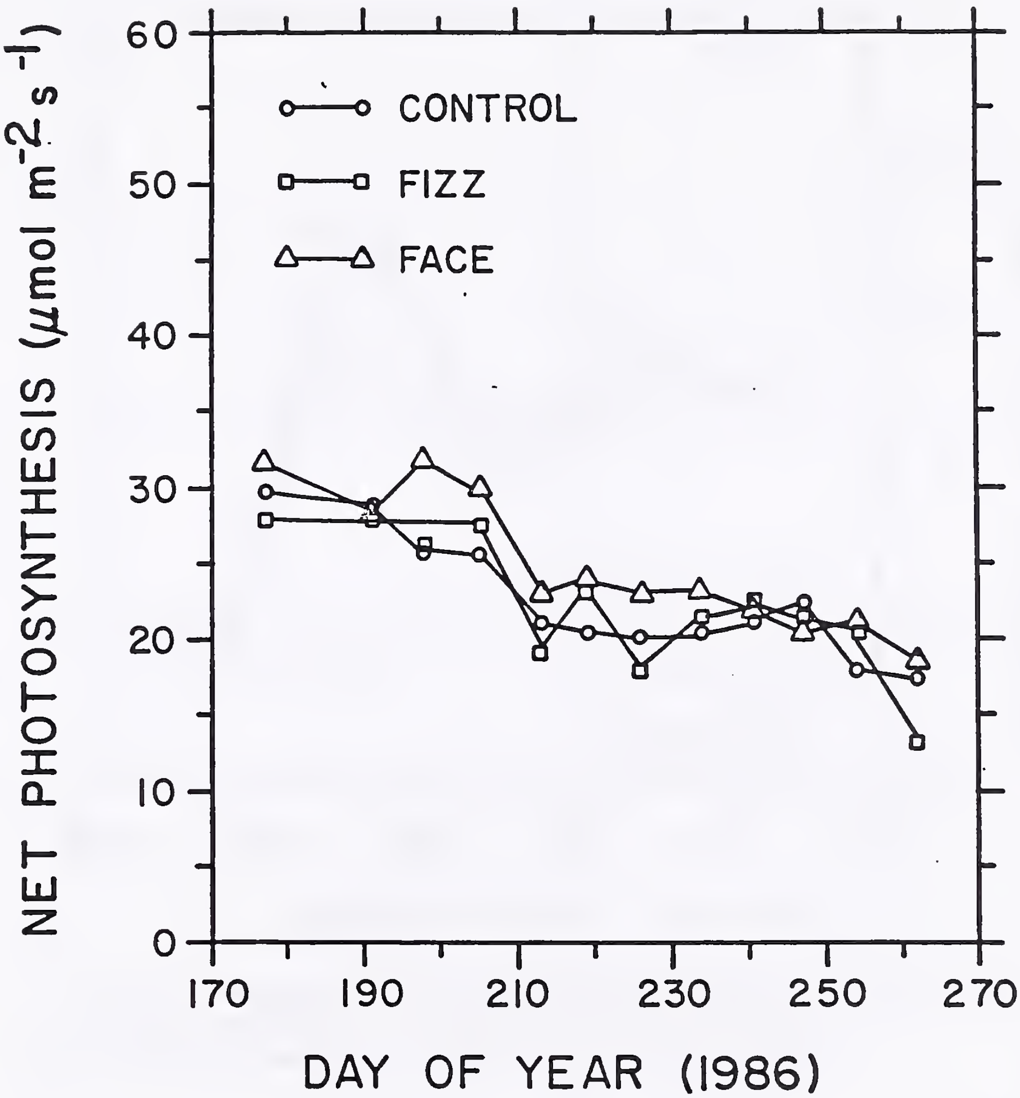

Figure 42. Net photosynthesis of cotton leaves vs day of year for the 1986 FIZZ/FACE experiment. Each data point is an average over 3 leaves per plot and 4 replicate plots.

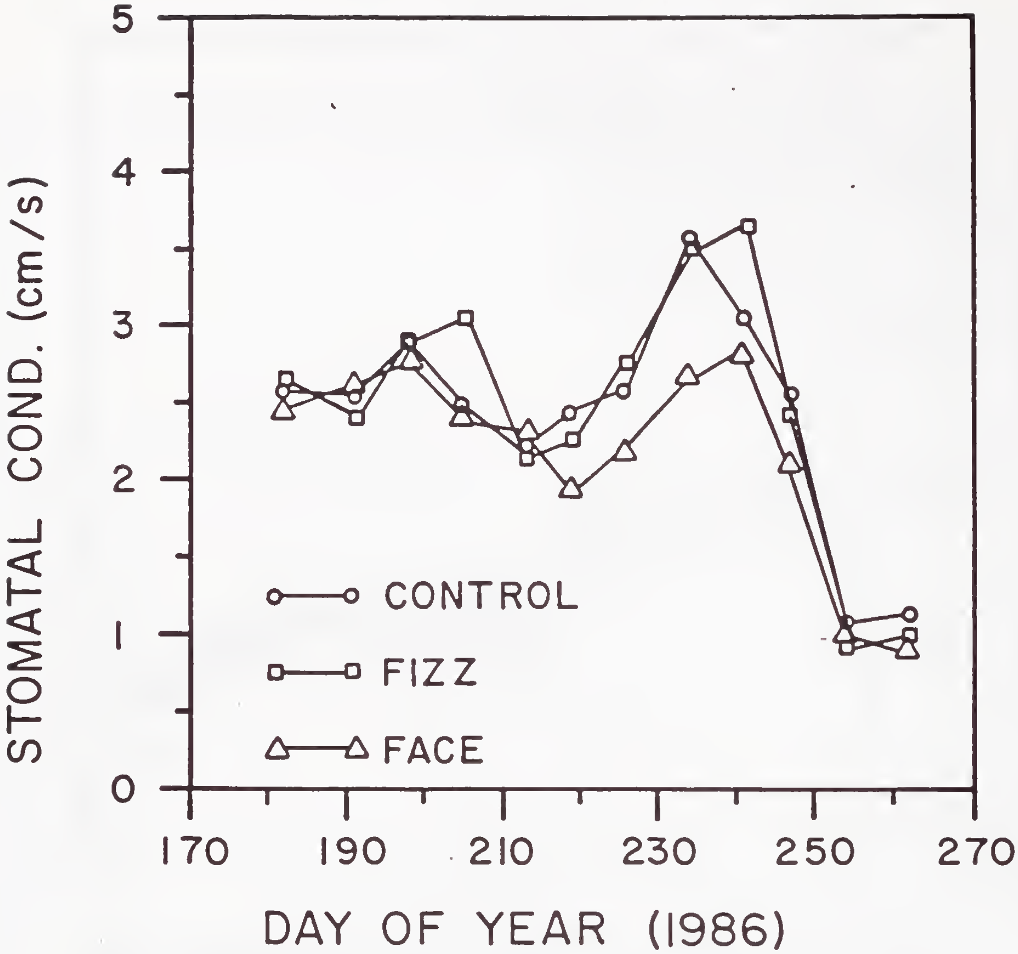

Figure 43. Stomatal conductance of cotton leaves for the 1986 FIZZ/FACE experiment. Each data point is an average over 3 leaves per plot and 4 replicate plots.

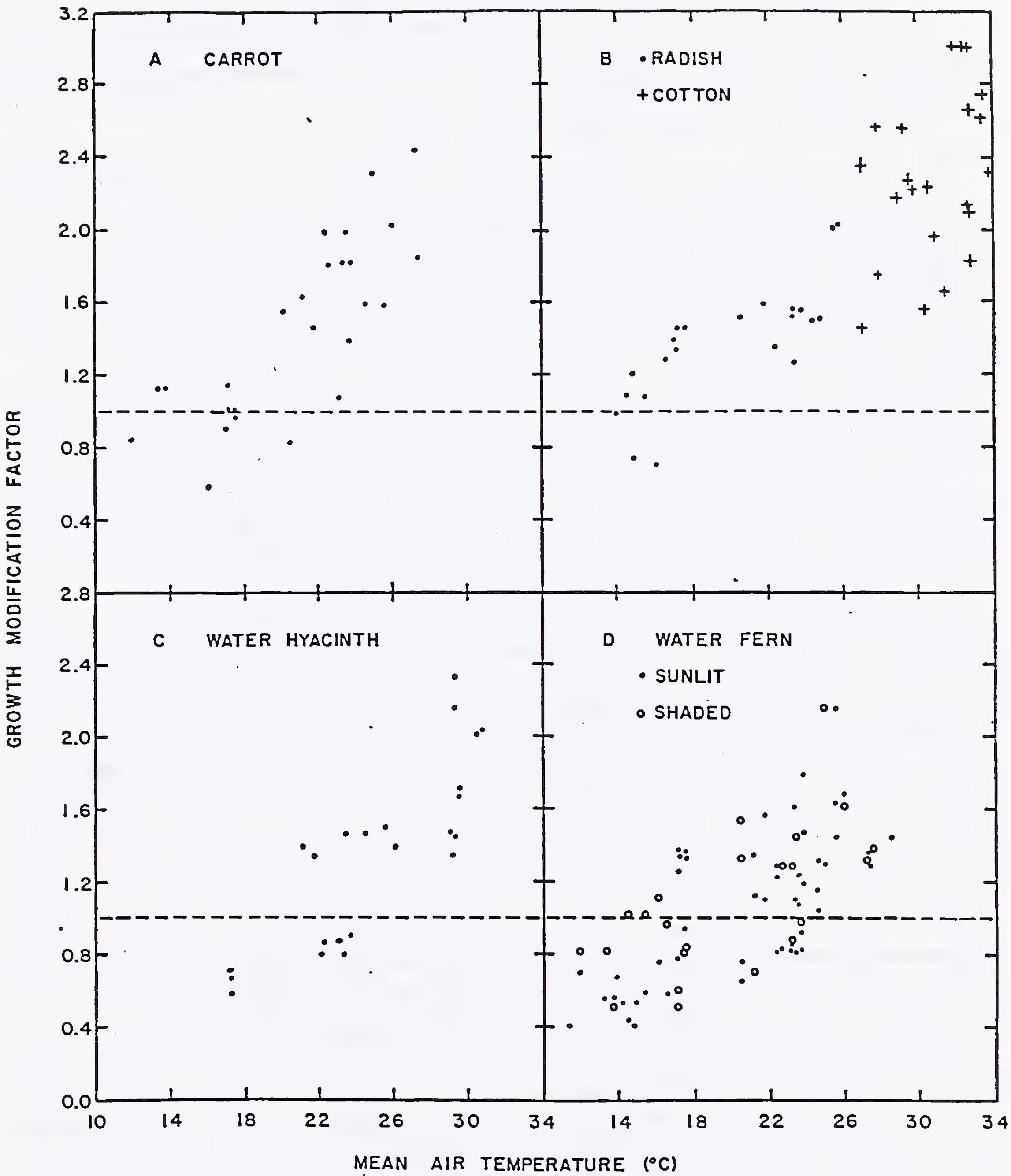

Figure 44. Plant growth modification factors resulting from a 300-ppm increase in atmospheric CO_2 concentration vs. mean air temperature for: A) carrot, B) radish and cotton, C) water hyacinth, and D) water fern, growing under natural sunlit conditions and under shaded conditions which filtered out 75 percent of the incoming sunlight.

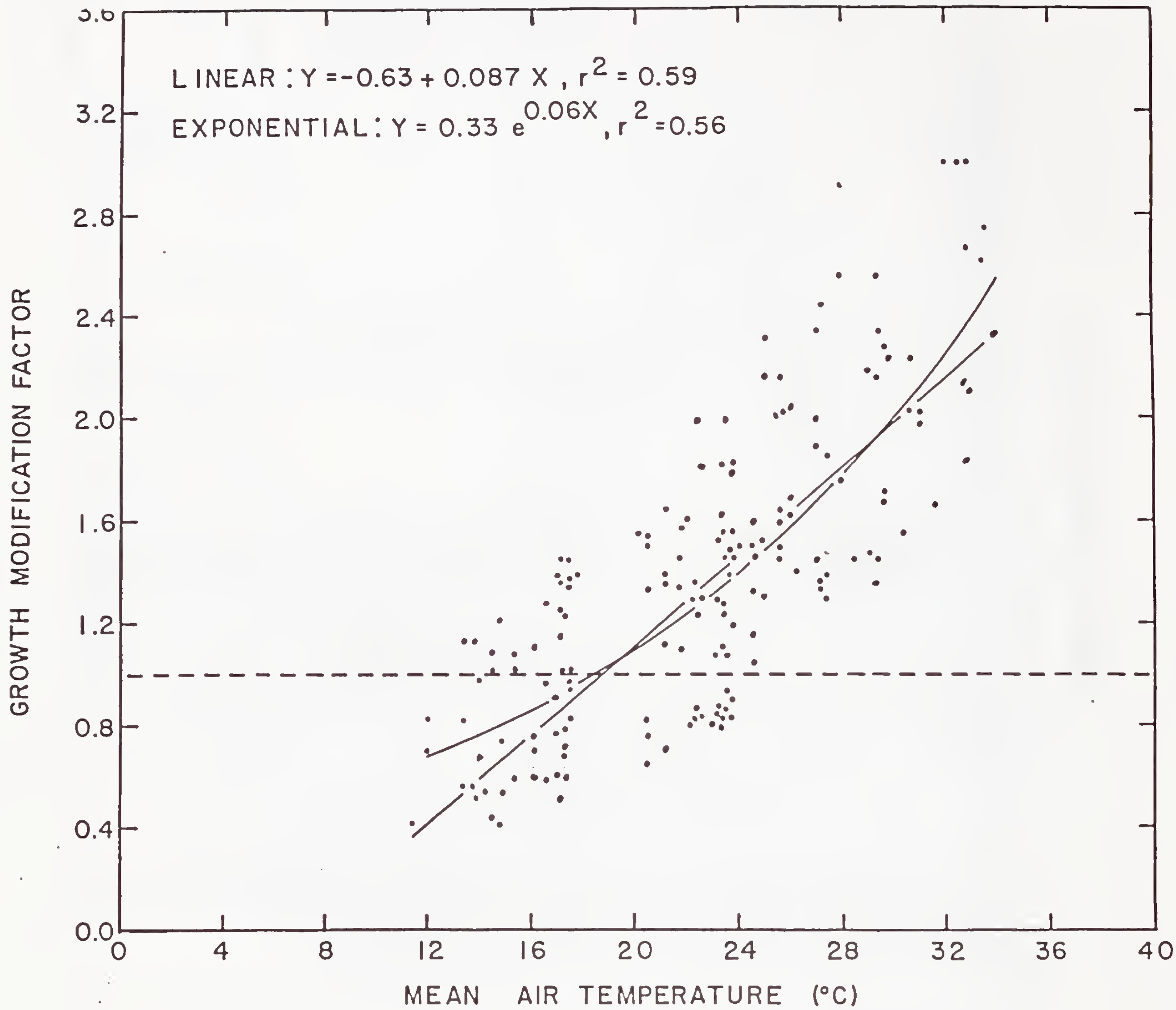

Figure 45. Plant growth modification factors resulting from a 300-ppm increase in atmospheric CO_2 concentration vs. mean air temperature for all five plant species studied.

TITLE: SOIL-PLANT-ATMOSPHERE INTERACTIONS AS RELATED TO WATER CONSERVATION AND CROP PRODUCTION

SPC: 6.1.03.1.c CRIS WORK UNIT: 5422-20760-008

INTRODUCTION

Our publication record this year (1986) is as good as ever with 35 manuscripts published, 14 in press, and 8 in journal review process. A few of the most interesting of these are reported in abstract form below. In addition to these, several experiments were conducted during the year and are discussed briefly before manuscripts are prepared.

Three papers deal with evapotranspiration (ET) from cropped surfaces. The first of these is concerned with the use of remote and ground-based measurements to estimate ET from agricultural fields of cotton, wheat and alfalfa. An analysis of a resistance energy balance method for estimating ET is described in two papers, with both of them presenting a sensitivity analysis of the model. Foliage temperature, as influenced by environmental factors and CO_2 enrichment, is discussed in two papers. The first demonstrates that the relationship between foliage air temperature differential and air vapor pressure deficit is indeed curvilinear, as theory predicts. In the second paper, it is shown that CO_2 enrichment actually causes foliage temperature to increase. In addition to these two papers dealing with CO_2, a third paper discusses the effects of CO_2 enrichment on the growth of a succulent plant, *Agave*. Two papers deal with measurement of reflectance using hand-held radiometers. All of these measurements require the use of standard reflectance panels, and the first paper shows how panels may be calibrated using the same radiometer used for field measurements. The second paper discusses how various spectral indices may be used to evaluate vegetation characteristics on arid rangelands. Of a more general nature, two papers discuss the general use of remotely sensed data to assess crop stress, and to develop an agrometeorological crop model. A final paper presents information of the effect of slope position on the microclimate, growth and yield of barley. Seven papers present information on the CO_2 climate issue and the proposed greenhouse effect, and the eighth deals with the controversy of nuclear winter.

In addition to these manuscripts, several preliminary reports were prepared with information on experiments recently completed. Two reports deal with evaluation of ET over large areas using remotely sensed measurements. The first of these took place over a 12-month period on agricultural fields of the Maricopa Agricultural Center (MAC). In the second report, an intensive 1-week experiment is detailed for the Owens Valley of California, which consists of native vegetation with incomplete canopy cover. Continuing the work at our Laboratory, an update is given for the final year of alfalfa grown in our lysimeter field. A short report is presented on the effects of topography on canopy reflectance, the result of a month-long study on rolling hills in

Italy. Our annual report concludes with a brief discussion of a user friendly computer program to calculate the Crop Water Stress Index (CWSI).

EVAPORATION

Jackson, R.D., Moran, M.S., Gay, L.W. and Raymond, L.H. Evaluating evaporation from field crops using airborne radiometry and ground-based meteorological data. Irrigation Science (in press)

Airborne measurements of reflected solar and emitted thermal radiation were combined with ground-based measurements of incoming solar radiation, air temperature, windspeed, and vapor pressure to calculate instantaneous evaporation (LE) rates using a form of the Penman equation. Estimates of evaporation over cotton, wheat, and alfalfa fields were obtained on 5 days during a one year period. A Bowen ratio apparatus, employed simultaneously, provided ground-based measurements of evaporation. Comparison of the airborne and ground techniques showed good agreement, with the greatest difference being about 12% for the instantaneous values. Estimates of daily (24 hour) evaporation were made from the instantaneous data. On three of the five days, the difference between the two techniques was less than 8%, with the greatest difference being 25%. The results demonstrate that airborne remote sensing techniques can be used to obtain spatially distributed values of evaporation over agricultural fields.

Choudhury, B.J., Reginato, R.J. and Idso, S.B. An analysis of infrared temperature observations over wheat and calculation of latent heat flux. Agric. For. Meteorol. 37:75-88.

From half-hourly averaged observations of net radiation, latent and soil heat fluxes over wheat, the sensible heat flux is calculated as the residual component of the surface energy balance. Then, the aerodynamic surface temperature is obtained by solving iteratively the aerodynamic equation for sensible heat flux, taking into consideration the bluff-body (differences in roughness height for heat and momentum exchange) and the stability (differences in surface and air temperatures) corrections to the aerodynamic resistance. The aerodynamic temperatures are found to be lower (higher) than the infrared thermometric observations under stable (unstable) atmospheric conditions. However, when the infrared temperatures were used in a resistance-energy balance equation to estimate the latent heat flux, then the estimated fluxes showed a high linear correlation r = 0.96) and a moderate standard error (47 W m^{-2}) under regression analysis with the observed fluxes.

Choudhury, B.J., Idso, S.B. and Reginato, R.J. Analysis of a resistance-energy balance method for estimating daily evaporation from wheat plots using one-time-of-day infrared temperature observations. Remote Sensing Environ. 29:253-268.

Accurate estimates of evaporation over field-scale or larger areas are needed in hydrologic studies, irrigation scheduling, and meteorology. Remotely sensed surface temperature might be used in a model to calculate evaporation. A resistance-energy balance model, which for combines an energy balance equation, the Penman-Monteith evaporation equation, and van den Honert's equation for water extraction by plant roots, is analyzed for estimating daily evaporation from wheat using post-noon canopy temperature measurements. Additional data requirements are half-hourly averages of solar radiation, air and dew point temperatures, and wind speed, along with reasonable estimates of canopy emissivity, albedo, height, and leaf area index. Evaporation fluxes were measured in the field by precision weighing lysimeters for well-watered and water-stressed wheat. Errors in computed daily evaporation were generally less than 10%, while errors in cumulative evaporation for 10 clear sky days were less than 5% for both well-watered and water-stressed wheat. Some results from sensitivity analysis of the model are also given.

FOLIAGE TEMPERATURE

Idso, S.B., Clawson, K.L. and Anderson, M.G. Foliage temperature: Effects of environmental factors with implications for plant water stress assessment and the CO_2/climate connection. Water Resources Res. 22(12):1702-1716.

Throughout the summer and fall of 1985, several day-long sets of foliage temperature measurements were obtained for healthy and potentially transpiring water hyacinth, cotton, and alfalfa plants growing in a sealed and unventilated greenhouse at Phoenix, AZ, along with concurrent measurements of air temperature, vapor pressure and net radiation, plus, in the case of the water hyacinths, leaf diffusion resistance measurements. Some data for these plants were additionally obtained out of doors under natural conditions, while dead, nontranspiring stands of alfalfa and water hyacinth were also monitored, both out-of-doors and within the greenhouse. Analyses of the data revealed that plant non-water-stressed baselines, i.e., plots of foliage-air temperature differential versus air vapor pressure deficit for potentially transpiring vegetation were (1) curvilinear, as opposed to the straight lines which have so often appeared to be the case with much smaller and restricted data sets, and (2) that these baselines are accurately described by basic theory, utilizing independently measured values of plant foliage and aerodynamic resistance to water vapor transport. These findings lead to some slight adjustments in the procedure for calculating the Idso-Jackson plant water stress index and they suggest that plants can adequately respond to much greater atmospheric demands for evaporation than what has been believed possible in the past. In addition, they demonstrate that the likely net radiation enhancement due to a doubling of the atmospheric carbon dioxide concentration will have little direct effect on vegetation temperatures, but that the antitranspirant effect of atmospheric CO_2 enrichment on foliage temperature may be substantial.

Idso, S.B., Kimball, B.A. and Anderson, M.G. Foliage temperature increases in water hyacinth caused by atmospheric CO_2 enrichment. Arch. Met. Geoph. Biolcl., Ser. B, 36:365-370.

Atmospheric CO_2 enrichment tends to induce partial stomatal closure in most higher plants. This phenomenon reduces per-unit-leaf-area plant transpirational water loss rates, which in turn leads to higher plant temperatures. Working in the field with water hyacinths maintained in open-top, clear-plastic wall, CO_2-enrichment chambers at Phoenix, AZ, we have quantified this relationship for a plant species which has been shown previously to react like most land plants in this regard. Our results indicate that in some parts of the world this non-greenhouse mechanism for surface temperature change may play an important role in determining future climate. Under sunlit and well-watered conditions conducive to active growth, for instance, we found water hyacinth foliage temperatures to increase by 2.7 K in response to a 300 to 600 ppm doubling of the atmospheric CO_2 concentration.

REFLECTANCE

Jackson, R.D., Moran, M.S., Slater, P.N. and Biggar, S.F. Field calibration of reference reflectance panels. Remote Sensing of Environment. (in press)

The measurement of radiation reflected from a surface must be accompanied by a near-simultaneous measurement of radiation reflected from a reference panel in order to calculate a bidirectional reflectance factor for the surface. Adequate calibration of the reference panel is necessary to assure valid reflectance-factor data. A procedure is described by which a reference panel can be calibrated with the sun as the irradiance source, with the component due to diffuse flux from the atmosphere subtracted from the total irradiance. Furthermore, the radiometer that is used for field measurements is also used as the calibration instrument. The reference panels are compared with a pressed polytetrafluoroethylene (halon) standard. The advantages of this procedure over conventional laboratory calibration methods are first, that the irradiance and viewing geometry is the same as is used in field measurements and second, that the needed equipment is available, or can be constructed, at most field research laboratories, including the press necessary to prepare the halon standard. A disadvantage of the method is that cloud-free sky conditions are required during the measurement period. The accuracy of the method is estimated to be 1%. Calibration results are given for four reference panels.

Huete, A.R. and Jackson, R.D. The suitability of spectral indices for evaluating vegetation characteristics of arid rangelands. Remote Sensing of Environment. (in press)

The spectral behavior of an arid, Lehmann lovegrass (Eragrostis lehmanniana), rangeland ecosystem with varying quantities of live, green

grass; senesced, yellow grass; gray litter; and different soil backgrounds was analyzed with a ground-based radiometer. The presence of standing yellow grass and gray litter were found to significantly alter the spectral reflectance of the soil background and the range canopy in the first four Thematic Mapper wavebands (0.45-0.52; 0.52-0.60; 0.63-0.69; 0.76-0.90 μm). These influences seriously hampered the utility of vegetation indices in assessing green phytomass levels. Gray litter was found to lower the greenness response of the green vegetation index (GVI) and perpendicular vegetation index (PVI) while having minimal influence on the near infrared to red ratio (NIR/red) or the normalizing difference vegetation index (NDVI). The presence of yellow, senesced grass increased the greenness response of plots with live vegetation. The soil background imposed a brightness influence whereby higher reflecting soils increased the greenness response of the GVI and PVI while decreasing the response of the NIR/red ratio and NDVI. Low amounts of emergent green grass (750 kg/ha) could not be detected in the presence of an overlying senesced grass stand. The results of this study show spectral vegetation indices to be unreliable measures of green phytomass in arid range ecosystems. A mixture model employing principal component analysis was used to extract the green vegetation signal, however, no improvement in green phytomass detection was observed. Apparently, the emergence of a green signal from range canopies is restricted by the scattering influences of standing senesced phytomass.

CROP MODELING

Jackson, R.D., Pinter, P.J., Jr., Reginato, R.J. and Idso, S.B. Detection and evaluation of plant stresses for crop management decisions. IEEE Trans. Geosci. Remote Sensing GE:24:99-106.

The ability to quantitatively assess crop conditions using remotely sensed data would not only improve yield forecasts but would also provide information that would be useful to farm managers in making day-to-day decisions. Experiments were conducted using ground-based radiometers to relate spectral response to crop canopy characteristics. It was found that radiometrically measured crop temperature, when compared with a reference temperature, was related to the degree of plant stress and could indicate the onset of stress. Reflectance based vegetation indices, on the other hand, were not sensitive to the onset of stress but were useful in evaluating the consequences of stress as expressed in changing quantities of green phytomass. Anatomical and physiological changes occur within plant cells when plants are stressed and increase the amount of reflected radiation. However, canopy geometrical changes may alter the amount of radiation that reaches a radiometer, complicating the interpretation of spectral response to stress. Timeliness, frequency of coverage, and resolution are three factors that must be considered when satellite-based sensors are used to evaluate crop conditions for farm management applications.

Wiegand, C.L., Richardson, A.J., Jackson, R.D., Pinter, P.J., Jr., Aase, J.K., Smika, D.E., Lautenschlager, L.F. and McMurtrey, J.E., III. Development of agrometeorological crop model inputs from remotely sensed information. IEEE Trans. on Geosci. & Remote Sensing GE24(1):90-98.

The goal of developing agrometeorological crop model inputs from remotely sensed information (AgRISTARS Early Warning Crop Condition Assessment Project Subtask 5 within the U.S. Department of Agriculture (USDA) provided a focus and a mission for crop spectral investigations that would have been lacking otherwise. Because the task has never been attempted before, much effort has gone into developing measurement and interpretation skill, convincing the scientific community of the validity and information content of the spectral measurements, and providing new understanding of the crop scenes viewed as affected by bidirectional, atmospheric, and soil background variations. Nonetheless, experiments conducted demonstrate that spectral vegetation indices (VI) a) are an excellent measure of the amount of green photosynthetically active tissue present in plant stands at any time during the season, and b) can reliably estimate leaf area index (LAI) and intercepted photosynthetically active radiation (IPAR)--two of the inputs needed in agrometeorological models. Progress was also made on using VI to quantify the effects of yield-detracting stresses on crop canopy development. In a historical perspective, these are significant accomplishments in a short time span. Spectral observations of fields from aircraft and satellite make direct checks on LAI and IPAR predicted by the agrometeorological models feasible and help extend the models to large areas. However, newness of the spectral interpretations, plus continual revisions in agrometeorological models and lack of feedback capability in them, have prevented the benefits of spectral inputs to agrometeorological models from being fully realized.

PLANT GROWTH

Whitman, C.E., Hatfield, J.L. and Reginato, R.J. Effect of slope position on the microclimate, growth, and yield of barley. Agron. J. 77:663-669.

Analyses of the relationship between microclimate data, yield and growth response usually have been conducted utilizing data collected on level terrain and in small experimental plots. A field study was conducted on 27 ha of undulating topography of a Sehorn-Balcolm complex soil (Entic Chromoxeret and Typic Xerochert) near Dunnigan, CA (38°48'121°58'W) during 1977-78 to evaluate the effect of slope position and microclimate differences on the growth and yield of barley (Hordeum vulgare L. cv. Briggs). The crop was planted on 3 to 9 Dec. 1977 at 112 kg ha^{-1} density in a 0.15-m row spacing. Sixteen sites were selected in the field prior to planting ranging from level to 36% slope with aspects from north- to south-facing slopes. At each site twice-weekly measurements were made of plant growth, i.e., height, number of green leaves, leaf area,, number of tillers, dry weight, and phenological stage, on 10

randomly selected plants. Yield and all yield components were measured on 20 1-m^2 samples at each site at the end of the experiment. Microclimatic data were measured at each site. The largest variations in crop development occurred prior to jointing and after anthesis. Both drainage and irradiance had large effects on plant growth, exhibited through differences in plant height, maximum leaf area, tiller survival, green leaves per plant, tillers per plant, relative growth rate, and dry matter production. A linear relationship was found between dry weight at the end of the season and intercepted radiation with a slope of 1.28 g MJ^{-1}. Dry matter production and yield were affected by irradiance and drainage. The data of 50% heading was inversely related to the final yield and suggested that delayed flowering was detrimental to grain production in the dryland conditions of the Central Valley.

CO_2-PLANTS

Idso, S.B., Kimball, B.A., Anderson, M.G. and Szarek, S.R. Growth response of a succulent plant, Agave vilmoriniana, to elevated CO_2. Plant Physiol. 80:796-797.

Large (about 200 grams dry weight) and small (about 5 grams dry weight) specimens of the leaf succulent Agave vilmoriniana Berger were grown outdoors at Phoenix, Arizona. Potted plants were maintained in open-top chambers constructed with clear, plastic wall material. Four CO_2 concentrations of 350, 560, 675, and 885 microliters per liter were used during two growth periods and two water treatments. Small and large plants were grown for 6 months, while a few large plants were grown for 1 year. Wet-treatment plants received water twice weekly, whereas dry-treatment plants received slightly more water than they would under natural conditions. Plant growth rates in all treatments were significantly different between small and large specimens, but not between 6 month and 1 year large plants. Only the dry-treatment plants exhibited statistically different growth rates between the CO_2 treatments. This productivity response was equivalent to a 28% and 3-fold increase when mathematically interpolated between CO_2 concentrations of 300 and 600 microliters per liter for large and small plants, respectively.

CO_2-CLIMATE

Idso, S.B. Industrial age leading to the greening of the Earth? Nature 320:22.

The enrichment of atmospheric CO_2 may greatly increase plant growth and development. A good test of this hypothesis is to be found in the secular variation of the seasonal CO_2 cycle amplitude. Does it increase with time in response to an increasing plant growth and decay cycle caused by the rising atmospheric CO_2 concentration? Recent years have seen several independent confirmations of this scenario. In light of this body of evidence, it is difficult to reject the conclusion that the predicted CO_2-induced "greening of the Earth" is upon us. I thus suggest

that the elusive "first detection" of global CO_2 effects has been accomplished, and that it is "biological, rather than climatic."

Idso, S.B. Nuclear winter and the greenhouse effect. Nature 321:122.

A timely and down-to-earth phenomenon to use as a means of calibration of the nuclear winter hypothesis is the CO_2 greenhouse effect; for it pertains to our own planet, is supposed to be happening now, and is itself predicted by the same climate models that produced the nuclear winter concept. Recent studies of Arctic and Northern Hemisphere temperature trends of the past century show that the prediction of the CO_2 greenhouse effect is fully an order-of-magnitude too large, so it is logical to assume that the nuclear winter prediction is similarly overestimated.

Idso, S.B. My response to the concluding 1984 issue of Climatic Change dealing with the CO_2/climate controversy. CO_2/Clim. Dial. 1(1):7-66.

Specific responses are made to several criticisms of my work on the subject of CO_2 and climate. I acknowledge and appropriately correct for several deficiencies in my previous work, clarify several areas of misunderstanding, and provide further substantiation for concepts and conclusions which I consider to remain valid in spite of the arguments raised against them. I additionally present a fairly objective analysis of the response of the scientific community in general to the ideas I have advocated relative to CO_2 and climate; and I conclude with some criticisms of my own directed against the Hamaker theory of CO_2-induced glaciation. It is my opinion that the combined results of these several topical analyses lend further credence to my long-standing posture relative to the effects of atmospheric CO_2 enrichment on climate, i.e., that there are none of any significance. Consequently, I conclude this review of my work and the criticisms raised against it as I concluded the very first paper I ever wrote on the topic: "a serious reconsideration of the whole CO_2-climate problem seems imperative."

Idso, S.B. Climate response times. CO_2/Clim. Dial. 1(1):69.

Most articles on the CO_2 greenhouse effect use the value 3.0 ± 1.5°C for the equilibrium warming of the Earth's mean surface air temperature in response to a 300 to 600 ppm doubling of the atmospheric CO_2 concentration. The references which they cite to support this figure all bear dates of 1983 or earlier. Since that time there have been several significant advances in our understanding of atmospheric process, which when incorporated into climate models have all tended to decrease the equilibrium warming. Taken together, the reduction amounts to a full order of magnitude.

Idso, S.B. Implications of sea level trends. CO_2/Clim. Dial. 1(1):70-71.

Recent experiments with atmospheric general circulation models lead to polar warmings and increases in polar precipitation. Comparing the magnitudes of these two processes, the latter is significantly greater than the former, such that a 3 K warming of the polar regions leads to a drop in sea level of 30 cm. Thus, the models themselves predict that the net effect of a CO_2-induced climate warming should be to lower sea levels and not to raise them. As a result, the observation of a global sea level rise could be argued to be evidence for a global climatic cooling.

Idso, S.B. Reconstructing past climates. CO_2/Clim. Dial. 1(1)72-75.

Present-day relations between species distribution and climate may not be representative of past relations, because of the fact that plants grow so much better under higher CO_2 concentrations and because of the fact that plants concurrently transpire much less water under higher CO_2 conditions -plant water use efficiency on a per-unit-leaf-area basis generally doubles for such a CO_2 concentration doubling. Consequently, since atmospheric CO_2 has varied so dramatically in the past--it is an almost unavoidable consequence that these well documented effects of atmospheric CO_2 on plant water use efficiency may significantly influence the floristic composition of natural plant communities, as well as their distributions in space and time and that this phenomenon, previously overlooked in the reconstruction of past climates, may be introducing large errors into our interpretation of several palaeoclimatic indicators.

Idso, S.B. Environmental effects of atmospheric CO_2 enrichment: Good news for the biosphere. CO_2/Clim. Dial. 1(2):16-28.

Based upon all of the available evidence, I conclude that there is currently no reason to expect any significant warming in the years to come as a result of the conventional greenhouse effect of the rising CO_2 content of Earth's atmosphere. However, there does appear to be ample reason to expect a positive response of the biosphere. Indeed, there are many indications that this global rejuvenation is already in progress.

Idso, S.B. My Response to Appendix B--"Review of the recent carbon dioxide-climate controversy"--of the DOE-sponsored state-of-the-art volume: The Potential Climatic Effects of Increasing Carbon Dioxide. CO_2/Clim. Dial. 1(2):29-37.

In the second of the four U.S. Department of Energy (DOE)-sponsored State-of-the-Art (SOA) volumes designed to summarize our understanding of the nature and potential consequences of the steadily increasing carbon dioxide (CO_2) content of Earth's atmosphere, Luther and Cess claim that my work on the CO_2-climate connection is "founded on various violations of the first law of thermodynamics," that it ignores "many important interactions of the climate system," and that it has "been

found to be based on improper assumptions or incorrect interpretations." In this short note I demonstrate that the criticisms of Luther and Cess are ill-founded and that my conclusions rest on a much firmer foundation than do those of the scientists I often refer to as "establishment climate modelers."

Idso, S.B. CO_2 and the Little Ice Age. CO_2/Clim. Dial. 1(2):38-39.

The observed warming of the past 100 years is almost invariably cited by most climate modelers as compelling evidence for the reality of the predicted CO_2-induced greenhouse effect. If, however, this warming is but the natural expression of Earth's recovery from the Little Ice Age, it provides no evidence whatsoever for the validity of the climate models.

MARICOPA AGRICULTURAL CENTER

An experiment was conducted at the University of Arizona's Maricopa Agricultural Center (MAC) during the period from April 1985 to June 1986 to study the use of remotely sensed data for farm management. The MAC Experiment was conceived with the objective of collecting a comprehensive set of remote and ground-based spectral data over agricultural fields whose agronomic properties were monitored. As the experiment progressed, more needs were identified and the list of participants multiplied. The experiment evolved into an intensive endeavor in which atmospheric measurements, aircraft-mounted and ground-based radiometer measurements and numerous soil and plant measurements were made on each day of the Landsat-5 overpass, weather and equipment permitting.

Participants in the experiment included personnel from the following agencies and departments:

University of Arizona (UA)
- Agricultural Engineering
- Maricopa Agricultural Center
- Office of Arid Lands Studies
- Optical Sciences Center
- School of Renewable Natural Resources
- Soil and Water Science

U.S. Department of Agriculture (USDA)
- U.S. Water Conservation Laboratory (USWCL)

U.S. Geological Survey (USGS)

Other agencies whose interest, assistance, and in some cases, funds, played a significant role in this experiment include NASA/Goddard Space Flight Center, USDA/WAOB and USDA/ARS.

The experimental site, the Maricopa Agricultural Center, is a 770 ha farm owned and operated by the University of Arizona and located about

48 km south of Phoenix. The farm is divided into a research and a demonstration area. The research farm is a 162 ha area of multiple plots that are used for small scale development projects. The demonstration farm is a 608 ha area, with fields up to 0.27 X 1.6 km in size, dedicated to demonstrating new farming techniques on a production scale. The demonstration area is ideal for high altitude remote sensing because the fields are large, the planting and irrigation schedules are well documented and field conditions such as crop type, plant height and soil moisture are monitored on a weekly basis.

Data Collection Methods

Data collection for the MAC Experiment was designed to coincide with the dates of the Landsat-5 overpasses. If the sun was unoccluded at the time of satellite overpass (approx. 1033 h MST), airborne and ground-based measurements were taken and Landsat-5 Thematic Mapper (TM) digital data were subsequently ordered by the USWCL, UA or USGS. The following data were collected: 1) Spectral [ground-based and aircraft-based]; 2) Meteorological; 3) Atmospheric; 4) Crop and soil and 5) Evaporation. In addition, a detailed soils map was prepared by UA personnel. These data are summarized in Table 1 and the data collection methods are described in the following sections.

Ground-based spectral data. Ground-based multispectral data were collected over bare soil and vegetated targets simultaneously with the satellite and aircraft overpasses. Two multiband radiometers, a Barnes 8-band Modular Multispectral Radiometer (MMR) and an Exotech 4-band radiometer, were used. Both instruments had 15 degree fields-of-view (FOV) for each spectral filter. Seven of the 8 MMR bands are similar to the seven TM bands and the 4 bands of the Exotech radiometer are similar to the first four bands of the TM radiometer. A single band infrared thermometer (IRT) was included in the mount with the 4-band radiometer in order to collect temperature data at a nadir look-angle. The IRT measures emitted radiation within a bandwidth of 8 to 14 μm. Nominal wavelength intervals for the MMR, the Exotech radiometer and Landsat TM are listed in Table 2.

The ground-based radiometers were suspended on a backpack type apparatus, to one side and slightly above the operator's shoulder. With this configuration, an extensive area on the ground could be monitored. Generally, the operator measured spectral data along a specified transect through a field, bracketing these measurements with readings over a calibrated reflectance panel. This pattern was repeated several times over a period of a half hour. In this way, target bidirectional reflectances could be calculated by ratioing the target voltages with the panel voltages, multiplied by the panel calibration factor.

Oblique-looking IRT data were collected over the same fields in which the 4-band radiometer and IRT were deployed. Surface temperatures were sampled in four cardinal directions at a 30 degree look angle from normal along two transect lines through several fields.

Aircraft-based spectral data. The aircraft-based spectral data were collected at a nominal altitude of 150 meters along a standard flight path over 11 fields. At this altitude, the radiometer and IRT viewed areas of about 40 meters diameter. Over a one mile transect, 18 to 24 data points were collected, depending on wind direction. The flight was scheduled to bracket the time of the satellite overpass.

The airborne sensors included a 4-band radiometer, a single band IRT and a camera. The multispectral radiometer and IRT were identical to the ground-based radiometer described earlier. Initially, a 35-mm camera was included in the airborne instrumentation to document the flight line. This camera was later replaced by a portable color video system. The system consisted of a video camera, a VCR and a character generator that wrote elapsed time to each frame of the video tape. Information on the tapes was used to identify the ground location and target composition of each spectral data sample.

A multispectral video camera (MSC) was added in April 1986. The MSC collected spectral data in 5 bands within the visible and near-IR wavelengths and one panchromatic band (.4 - .7 μm).

The instruments were installed on a mount that could be positioned to provide a view normal to the ground surface with the aircraft door propped open. The sensors were controlled by a sample-and-hold device that triggered the radiometer and the IRT and sent an audio signal to the video system. This device ensured that the same ground target was sampled by all instruments at the same time. A small data logger signaled the sample-and-hold device to collect a sample every 2 seconds. The logger stored the time of sampling (to 0.0001 hr) and the voltage readings of all the sensors in resident memory. The entire system was operated by one person who positioned the instruments and pressed a toggle switch to start and stop data collection.

TM spectral data. The Landsat-5 satellite passes over MAC farm every 16 days on a polar orbit, 9 degrees East of North. The TM radiometer collects spectral data in 7 bands at a pixel resolution of about 30 meters on a side in the visible, near-IR and mid-IR bands. Thermal data are collected at a coarser (120 m) resolution. Figure 1 is a graphic representation of the pixel resolution of TM data and the airborne radiometer data in relation to field size over a portion of MAC farm.

Geometric and radiometric distortion are inherent in TM data due to characteristics of the sensing and recording systems as well as atmospheric effects. Limited data corrections are performed at the EROS Data Center, where customer products are generated. Radiometric correction, based on gain and bias values determined by an internal calibration lamp, are applied to the data in two forms. For "A" tapes, data have been fully corrected radiometrically while maintaining the sensor-to-line relationship throughout the scene. For "P" tapes, the radiometric correction is combined with a geometric resampling that

causes the scan lines to lose their one-to-one identification with a unique detector.

Both P and A tapes have been ordered for this experiment (Table 1), though A tapes are preferable for most applications because the data have not been resampled. This is particularly true in the thermal channel where the resampling procedure converts each 120-meter pixel into 16 30-meter pixels and then performs a cubic convolution over all pixels in the scene. The results are an image in which digital data are "smoothed" and the information contained in the original 120-meter pixels is lost. This produces confusing results in an area such as MAC farm where the fields widths are only slightly larger than the 120-meter pixels.

Meteorological data. Measurements of wind speed, solar irradiance, and wet and dry bulb air temperature were collected using two portable meteorological stations erected during the time of each aircraft/satellite overpass. One station included a solar pyranometer, a thermocouple-based psychrometer and a cup anemometer (at 1.5 m). An autologger was initialized to collect instantaneous voltage readings from all sensors at 6-second intervals throughout the measurement period. Fluctuations of the 6 second wind speed values were reduced by smoothing the data with a 30 point (3 minute) running average. The second station collected similar data averaged over a 5-minute period.

Atmospheric data. In order to compare TM spectral data collected on different days, the digital numbers must be corrected for atmospheric effects. Precise atmospheric measurements were made at MAC farm on the morning of each overpass, weather permitting. A multiband solar radiometer was used to measure transmitted solar irradiance every three minutes, beginning 1/2 hour after sunrise and ending at solar noon. The radiometer had 12 spectral band filters and two detectors within a range of 0.4 μm to 2.5 μm. The optical depth within each band was determined by using the Langely plot technique, which is a plot of solar irradiance as a function of airmass. These results will be used to correct the TM data for atmospheric effects using radiative transfer programs.

By invoking the absolute calibration of TM, as determined at White Sands, New Mexico or from TM internal-calibrator data, we will be able to predict ground reflectance values from the digital counts in the TM image. A comparison of these predicted values with ground reflectance measurements made with the Barnes and Exotech radiometers will allow us to assess the accuracy of this procedure.

Crop and soil data. Crop and soil conditions were monitored on a regular basis by UA MAC personnel. Daily records were kept of field operations, such as irrigations, chemical applications and tractor operation. Weekly records included plant height, crop color and health, length between nodes, and soil moisture. When the cotton crop was mature, the number of developed bolls and percent of open bolls were also recorded.

Weekly records were collected according to a sampling scheme based on soil variation, resulting in about one sample every four acres. Each sample measurement was a composite of six measurements at the site.

These data were entered into a database in columnar format for computer access by date or data type. Work is underway to convert the columnar data to spatially-continuous data in image format so that field information can be combined with TM spectral data in an image processing environment.

On the day of a Landsat-5 overpass, an inventory of crop and field status was conducted by USGS personnel. Every field was visited and field notes were logged about crop type and stage of development, soil roughness and moisture and within field variability. In addition, photographic records were collected to accompany notes and document particular field conditions.

Detailed soils mapping is being completed for the MAC farm. Samples of the surface horizons were collected on a 100-meter grid sampling system for the entire farm and numerous physical parameters were measured on each sample. Sub-surface samples were also collected on a less extensive sampling scheme. In situ reflectance data were also collected over bare soil fields of varying surface conditions. All data will be spatially registered in order to provide useful crop/soil interpretative information for analyses of spectral data.

Evaporation data. A Bowen ratio apparatus was employed at MAC farm on selected days to estimate total evaporation over cropped land. The Bowen ratio apparatus consisted of a psychrometer exchange mast, a net radiometer, a soil heat flux disc, anemometer and a data acquisition and processing system. The psychrometer mast interchanged the sensors at six minute intervals, allowing evaporation calculations to be made on 12 minute averages. Daily evaporation rates were measured by summing the 12 minute values collected over a 24 hour period.

The Bowen ratio apparatus provided data for comparison of ground-based methods with a remote method for estimation of evaporation. The remote method combined aircraft-based measurements of reflected solar and emitted thermal radiation with ground-based measurements of incoming solar radiation, wind speed and vapor pressure to estimate the spatial distribution of evaporation.

Results

Data collection for the MAC Experiment was completed in June 1986. Over a 15 month period from Apr 18, 1985 to June 24, 1986, there were 28 possible overpass dates. Of these, 10 dates were eliminated: 8 due to cloudy weather and 2 due to personal scheduling conflicts. Of the 18 remaining dates, we were only able to acquire 10 TM scenes. Scenes from the other dates were unavailable due to satellite orbit adjusts and

conflict with space shuttle flights (the receiver for TM data is also used for shuttle transmissions).

Over the period in which we collected airborne radiometer data, from June 21, 1985 to June 24, 1986, a total of 17 sets of spectral data were collected. Three sets of data are considered unacceptable due to partial, intermittent cloud cover during measurements. The majority of the data sets were of excellent quality, with the exception of dates in September and October when we were testing the sample-and-hold device. On those dates, high quality spectral data were collected but it was interrupted by intermittent system failure. On one occasion, the system malfunctions caused the accompanying photographic data to be flawed.

The ground-based data are abundant and generally of excellent quality, as is evident in Table 1. Meteorological data were collected on all dates in the experiment, usually at both 6 second intervals and 5 minute averages. Photographs of field conditions and equipment were archived for all overpass days. The Bowen ratio equipment was successfully deployed on 8 dates in fields of wheat, cotton, alfalfa and bare soil.

Ground-based spectral data are available in various wavelength bands over wheat, alfalfa, cotton and bare soil for dates throughout the year. Spectral data in the visible, near-IR and thermal wavelength bands were collected over a single field of alfalfa on 14 dates over a one-year period. Since alfalfa is commonly harvested at least six times a year in Arizona, this data set encompassed vegetation at various stages of growth and cover.

Spectral data in the visible, near-IR, mid-IR and thermal wavelengths were collected over crops of wheat, cotton, alfalfa and bare soil. An attempt was made to follow each crop through its growth cycle. Thus, we collected data over cotton from May to August, wheat from March to May and alfalfa through the winter. Data were also collected over bare soil of varying roughnesses, from smooth laser-leveled fields to fields freshly tilled. In addition to providing information about the spectral response of bare soils, data over fallow fields provided a large uniform area for cross-calibration between ground-, aircraft- and satellite-based instruments.

On the final day of data collection, June 24, 1986, measurements were made continuously over a half day, from 0800 until 1230 h. This intensive collection resulted in 6 sets of aircraft-based spectral data and several sets of ground-based spectral data over alfalfa, immature cotton and soil at four different roughnesses. Of particular interest were two cotton fields of 50% canopy cover-- one in east/west rows and one in north/south rows. Influence of row orientation on spectral response is one of the areas of study this project hopes to address.

Concluding Remarks

Cooperative data collection efforts at the MAC farm have resulted in an unique, high quality data set. Definitive, detailed reports on the results of data analysis will be forthcoming from individual participants in the MAC Experiment. Though specific data have been processed and archived by the agency most involved in data collection, the data set as a whole is accessible to all participants and to other interested groups for pertinent research.

OWENS VALLEY

Recently, a technique was developed that uses remotely sensed data in conjunction with ground-based data to estimate the spatial distribution of evaporation. This technique has been shown to yield values of LE in good agreement with ground-based Bowen ratio data for agricultural fields. It has not been tested under conditions of unevenly vegetated surfaces such as rangeland where exposed soil temperatures may greatly exceed vegetation temperatures.

Airborne radiometers can rapidly obtain data over rather large areas, encompassing a number of sites having considerably different evaporation rates. Evaporation rates calculated from these data are essentially instantaneous values. Ground-based methods for measuring evaporation, such as the Bowen ratio record data continuously with time, but the values apply only to an area surrounding the apparatus that is evaporating at the same rate. This makes a comparison of the methods difficult because, during a particular measurement sequence, only one value from each method is coincident in both space and time.

This report presents the results of an experiment in which airborne- and ground-based radiometers were used to obtain reflected radiation and surface temperatures over three sites (designated 2, 5, and 10) in the Owens Valley. These data, combined with ground-based measurements of incoming solar radiation, air temperature, vapor pressure, and windspeed, provided a means of estimating the spatial distribution of evaporation over three sites in the Owens Valley.

Background of Remote Method

Calculation of evaporation with remote inputs depends upon the evaluation of net radiation (R_n), soil heat flux (G), and sensible heat flux (H), as related by the energy balance for a surface,

$$LE = R_n - G - H, \tag{1}$$

where LE is the latent heat flux. All terms are in units of W m^{-2}.

Net radiation. Net radiation is the sum of incoming and outgoing radiant fluxes, i.e.,

$$R_n = R_{S\downarrow} - R_{S\uparrow} + R_{L\downarrow} - R_{L\uparrow} \quad (2)$$

where the subscripts S and L signify solar (shortwave) radiation (0.15 to 4 mm) and longwave radiation (>4 mm) respectively. The arrows indicate the flux direction.

The incoming terms ($R_{S\downarrow}$ and $R_{L\uparrow}$) can be measured with traditional ground-based instruments and the data extrapolated radially for some distance from the point of measurement, and that the outgoing terms ($R_{S\uparrow}$ and $R_{L\downarrow}$) can be obtained from multispectral data. It is proposed that $R_{S\downarrow}$ be measured with a calibrated pyranometer sensitive to radiation over most of the solar spectrum. The area over which a point measurement of $R_{S\downarrow}$ can be extrapolated would be governed largely by the areal uniformity of the scattering and absorbing properties of the atmosphere.

Only part of the reflected solar term, $R_{S\uparrow}$, is measured with a multispectral radiometer. Since each radiometer measures a different fraction of the total reflected radiation, the total must be estimated from the partial. A radiative transfer model was used to calculate the irradiance at the earth's surface for a number of atmospheric scattering and absorption conditions. Measured spectral reflectance distributions for 14 different surface conditions (bare soil to full green canopy) were used along with the calculated irradiance data to determine the ratio of the radiation measured by a multispectral radiometer to the total reflected solar radiation (the P/T ratio).

The incoming longwave radiation, $R_{L\downarrow}$, can be estimated from ground-based measurements of air temperature and vapor pressure using the relation $RL\downarrow = \varepsilon_a \sigma T_a^4$, where $\varepsilon a = 1.24(e_o/T_a)^{1/7}$, σ = the Stefan-Boltzmann constant, T_a = air temperature (K), and e_o = vapor pressure (mb). Inputs needed to calculate this term are from ground-based measurements.

The outgoing longwave radiation, $R_{L\uparrow}$, is obtained from the remotely measured surface temperature, $R_{L\uparrow} = \varepsilon_s \sigma T_s^4$, where ε_s = surface emissivity, and T_s = surface temperature (K). (We have ignored the small contribution to $R_{L\uparrow}$ by reflected sky radiation.) At this point, it is not necessary to evaluate ε_s. If the thermal radiometer is calibrated with reference to a blackbody whose emissivity is near unity, then the surface emissivities would be implicit in the apparent surface temperatures and would cancel when the emitted longwave energy is calculated.

Soil heat flux. Soil heat flux is traditionally measured with sensors buried just beneath the soil surface. This flux is dependent on whether the surface is wet or dry, bare or vegetated, and therefore, a ground-based measurement should not be extrapolated areally. A remote measurement of G is not possible, but several relationships between G and R_n have been proposed. Several studies have shown that G is attenuated by

vegetation, being as high as $0.5R_n$ for dry bare soil and as low as $0.1R_n$ for full vegetative cover.

Vegetative cover can be assessed remotely by using spectral data in the red and near-infrared (IR) wavebands. The normalized difference is a combination of these bands. That is, ND=(IR-red)/(IR+red). This spectral vegetation index is more sensitive to low density vegetation than other indices such as the simple ratio IR/red. We developed a relation between the ND and G/R_n based on data collected at sites 2 and 10 on DOY 156. This relation is

$$G/R_n = -0.1009ND + 0.1748, \tag{3}$$

where G was measured at each site with soil heats flux sensors buried at 1 cm below the surface. The data are presented in Fig. 2. Each symbol in the figure represents the output from three sensors. R_n was calculated using remote spectral measurements and ground-based meteorological measurements. The ND was obtained from spectral reflectance measurements collected with both ground- and aircraft-based radiometers. The data were collected over a six hour period.

Equation (3) was tested using a second set of data also collected at sites 2 and 10, but on DOY 154 (Fig. 3). The correlation coefficient was 0.9, indicating that the relation provides an adequate estimate of G/R_n from spectral data.

Sensible heat flux. The final term to be evaluated is the sensible heat flux (H), which can be expressed as,

$$H = \rho c_p(T_s - T_a)/r_a, \tag{4}$$

where ρc_p is the volumetric heat capacity (J m^{-3} C^{-1}), and r_a is a stability corrected aerodynamic resistance (s m^{-1}).

Up to this point the equations apply to a uniformly vegetated surface, (with the exception of the soil heat flux) a condition not existing in the Owens Valley. The vegetation at site 2 is far from uniformly distributed. The treatment of this partial canopy condition has received some theoretical attention by considering that the aerodynamic resistance in equation (4) is composed of momentum resistance and an additional resistance to transfer of heat and water vapor. However, use of the temperature difference (T_s-T_a) in equation (4) also assumes that the surface is at a uniform temperature T_s and that evaporation is spatially uniform. With a surface consisting of a partial canopy, the vegetation may be at one temperature, the soil at another, with the composite temperature measured and entered into equation (4). This problem has not been successfully approached theoretically.

In this report, two approaches will be used. Evaporation will be calculated using recent theoretical developments concerning the inclusion of

resistance for heat transfer, and an empirical adjustment to (T_s-T_a) in an attempt to approximate the temperature difference that drives evaporation from vegetative surfaces under conditions of partial canopy.

Theoretical approach. r_a can be expressed by the relation

$$r_a = [B^{-1} + k^{-1}\ln(z-d)/z_o)]/U_*, \tag{5}$$

where k is von Karman's constant (0.4, unitless), z the height (m) above the surface at which the windspeed and air temperatures are measured, d the displacement height (m), and z_o the roughness length for momentum (m). The friction velocity (U_*) is solved by iteration. For unstable conditions, $[(T_s-T_a)]>0$,

$$U_* = (kU)/\{\ln[(z-d)/z_o] - \psi\}, \tag{6}$$

where U is the windspeed (m s^{-1}), and y is a complex expression that includes U_* and the temperature difference, thus the necessity for an iterative solution.

The parameter B^{-1} is essentially an additional resistance to the transfer of heat above that for momentum.

Values of B^{-1} are dependent on the roughness of the surface and the permeability of the roughness obstacles. For this experiment, B^{-1} was estimated using equations developed from empirical data. For site 10, B^{-1} was estimated to be 7.5, corresponding to results over grassland. For site 5, B^{-1} was 10, corresponding to a "permeable rough" situation. Site 5 was particularly complex because it consisted of large roughness obstacles scattered sparingly across bare soil. In such a situation, B^{-1} is dependent upon temperature and cannot be approximated by a constant. From data collected at Site 2 on DOYs 154 and 156 we developed the relation

$$B^{-1} = -1.9397\text{x}10^{-7}(z_{o+})^2 + 4.5191\text{x}10^{-3}(z_{o+}) - 7.3914 \tag{7}$$

with a correlation coefficient (r^2) of 0.84. Here, $z_{o+} = (U_*z_o)/\nu$ with ν being the kinematic viscosity of air (m^2 s^{-1}).

Empirical approach. For the empirical approach we begin with an expression for the aerodynamic resistance that does not require iteration. We have

$$r_a = \{\ln[(z-d+z_o)/z_o]/k\}^2\{-15Ri/[1+C(-Ri)^{1/2}]\}-1/U, \tag{8}$$

for the unstable case. In equation (8), Ri is the Richardson number $[Ri=g(T_a-T_s)(z-d)/T_aU^2]$, g the acceleration due to gravity (m s^{-2}), and $C=75k^2[(z-d+z_o)/z_o]^{1/2}/\{\ln[(z-d+z_o)/z_o]\}^2$.

For uniformly vegetated areas, z_o and d can be estimated from the vegetation height. For agricultural fields, values of z_o=0.05h and d=0.63h (h being the plant height) have been used. When the vegetation is non-uniform, these values are not appropriate. The apparent displacement height d would be less for the non-uniform case than for uniform areas. We used the relation $d=0.63hC_b$, where C_b is the fraction of vegetative cover. Thus, at complete cover, and at zero cover, the relation reduces to the form for uniform cover.

The roughness length z_o must also be adjusted for non-uniform, partial cover. We used the relation $z_o=0.05h[1-C_b(C_b-1)]$, which reduces to the uniform case at C_b=1 and C_b=0, but is a maximum at C_b=0.5.

In equation (4) the sensible heat (H) is directly proportional to the temperature difference (T_s-T_a). This relationship does not hold for the partial canopy case. Consider an area in which a number of shrubs having a deep root system cover only part of the surface. The composite temperature as measured from an aircraft would be dominated by the hot bare soil, though the leaf surface at which the evaporation takes place may be at a much lower temperature. The temperature difference to be used in equation (4) should be considerably less than the measured composite temperature. We approximated this condition by raising (T_s-T_a) to a power less than one, but dependent on the amount of vegetative cover, reducing to 1 at full cover and at zero cover. We developed the relation α=1-3.2ND(1-ND), and replaced the temperature difference in equation (4) by $(T_s-T_a)^a$. An exact treatment of this condition is beyond the scope of this report.

Estimation of daily totals of LE from instantaneous values

The daily course of LE would generally follow the trend of solar radiation throughout the daylight period. They showed that, for cloudless skies, the ratio of total daily solar radiation (R_d) to an instantaneous value (R_i) could be approximated by the relation,

$$R_d/R_i = 2N/[q\sin(qt/N)], \tag{9}$$

where t is the time starting at sunrise and N is the daylength (in hours). With the assumption that LEd/LEi = R_d/R_i, equation (7) allows a factor to be calculated to convert to daily totals from instantaneous values of LE for the time of day that the instantaneous measurement was made. An additional assumption was that environmental factors such as windspeed be relatively constant over the daily period.

Procedure

The three sites represented areas of varying vegetative cover and evaporation rates. Site 2 was characterized by tall, scattered bushes covering about 30% of the area. In general, little grass or annual vegetation cover was present at this site. Site 5 was similar to site 2

though the bushes tended to be shorter and vegetation cover was more sparse (about 20% cover). Site 10 was a grassland of about 75% vegetative cover consisting of perennial and annual grasses with scattered, small bushes. The area surrounding the grass area was similar to site 5, having scattered bushes.

Ground-based radiometric data were collected in a 60 X 60 m target area chosen to represent the vegetation type at each site. Reflectance measurements were recorded along 12 transects in the east/west and north/south directions within the target area. Meteorological data were collected throughout the day at a location immediately adjacent to the target area. Bowen ratio and eddy correlation instruments were located nearby the target area, within the same vegetation type. Ground-based radiometric and meteorological data were not collected at site 5 during the first two days of the experiment due to a shortage of personnel.

Airborne radiometer data were collected over the 3 sites at three times during each day. The flights were scheduled for 1030 h, 1230 h, and 1500 h, at site 10. Ground-based reflectance measurements and meteorological data were collected at the time of the aircraft overpass at each site.

The aircraft covered two one-mile flight lines at each site. The two lines were perpendicular to each other, crossing at the target site. The remote sensing equipment aboard the aircraft consisted of a four-band multispectral radiometer, a single band thermal infrared thermometer, and a video camera. In flight, the instruments viewed normal to the surface with a nominal 15; field of view. At an altitude of about 150 m, a circle of about 40 m diameter was observed on the ground. On the approach to a flight line over a site, a data logger was triggered to record the output from the five channels and the time (to 0.0001 hour) at 2 sec intervals. A character generator on the video system recorded the elapsed time on each frame. The video time and data logger time were used to identify the video frame corresponding to a particular sample. The video provided ground location for each sample and information on the composition of the surface.

The four-band radiometer data was converted to radiance values by use of calibration factors provided by the manufacturer. The radiances of the four bands were summed and divided by the P/T ratio (0.32), to yield values of $R_{S\uparrow}$ (equation 2). The surface temperatures measured with the infrared radiometer were used to calculate $R_{L\uparrow}$, and corrected for emissivity (ε = 0.985 for site 10, 0.975 for site 2, and 0.970 for site 5) to obtain the temperature difference ($T_s - T_a$). Soil heat flux was estimated from R_n using the spectral data to calculate the fraction G/R_n (equation 3).

A portable micrometeorological station, located at sites 2 and 10 recorded incoming solar radiation, wet and dry bulb air temperature, and windspeed at 6 sec intervals. Fluctuations of the 6 sec windspeed

values were reduced by smoothing the data with a 30 point (3 min) running average. These measurements provided data for the calculation of $R_{S\downarrow}$, $R_{L\downarrow}$, and r_a, of equations (2), (4), (5), and (8). The instantaneous evaporation, LE_i, was calculated using equation (1).

Results and Discussion

Net radiation calculated from the remote measurements correlated well with values measured with ground-based net radiometers. Soil heat flux values estimated with the remote method were in substantial agreement with the values obtained using heat flux plates.

Daily evaporation rates of natural vegetation at Owens Valley were estimated on four consecutive days using both the theoretical and the empirical approaches. Measurements on the third day were hampered by heavy cirrus and cumulus cloud cover. Since estimates of daily LE from instantaneous values are based on the assumption that the daily course of radiation can be described by a sine function, the daily estimates are unreliable on cloudy days. Thus, results from only three of four days are reported here (Table 2).

On Day of year (DOY) 153 the theoretical and empirical approaches yielded similar values of LE_d. On this day surface soil temperatures were relatively low due to recent rains. On the subsequent days the surface temperature became increasingly warmer than the air, and the theoretical values of LEd decreased. We attribute this decrease in LE_d to the fact that the temperature difference is not adequately accounted for in the theoretical approach. Since the vegetation, for the most part, had roots reaching the water table, the evaporation rate would not be expected to decrease with time at the rate shown by the theoretical calculations. The empirical approach yielded values of LE_d that were relatively constant for the 4 days of measurements, a result also found using the Bowen ratio and the eddy correlation methods. Subsequent discussion will be confined to results from the empirical approach.

Remote estimates of daily evaporation at site 10 were significantly higher than at sites 2 and 5. This result was expected since the water table at site 10 was estimated to be 1 m below the surface, compared to 3.4 m and 3 m at sites 2 and 5. Furthermore, the vegetative cover at site 10 was more lush and more extensive than at either site 2 or 5. Evaporation at site 2 was slightly higher than at site 5, though insufficient data was collected at site 5 to make a definitive conclusion.

Estimates of LE_d within a 1 mile square area varied significantly depending on vegetation cover and density. A good example of this variation was seen along the east/west transect at site 2. On day 156, the LE_d estimates along a single transect varied from 0 to 7.2 (Figure 4). The extreme low and high values of LE_d corresponded to a region of dry, scrub vegetation and an area of standing water covered by tall trees and sedge, respectively. Values of LE_d based on Bowen ratio and

eddy correlation measurements at the target site are represented in Figure 4 by the asterisk and open circle, respectively.

At site 10, the east/west transect followed the length of a moist creekbed, deviating slightly from the creek at the east end. The north/south flight line started and ended over dry rangeland vegetation, crossing the creek and grassland at the midpoint of the flight line. The variation in LEd over these flight lines and results from Bowen ratio and eddy correlation methods are shown in Fig. 5.

When comparing the Bowen ratio and eddy correlation data with the remote values, it should be kept in mind that the flight lines did not consistently pass directly over the ground-based equipment. This is particularly important at sites 2 and 10, where the vegetation at the site where the ground measurements were made was considerably different than the vegetation surrounding the site. Therefore the remote data may have been more influenced by the surrounding area than were the ground-based measurements, thus leading to differing values of LE_d.

Concluding Remarks

The results reported here indicate that an airborne remote sensing technique will yield reasonable values of evaporation from arid rangeland. The remote method developed for use over uniform agricultural fields produced reasonable estimates of net radiation and soil heat flux when applied to a heterogeneous landscape at Owens Valley. Sensible heat flux, based on theoretical models, was overestimated at all sites due to measurement of high surface temperatures that were dominated by the hot soil surface rather than the transpiring vegetation. An empirical approach was developed to adjust the surface-air temperature difference in proportion to the amount of vegetation present at the site. This approach produced values of evaporation that were in good agreement with values obtained with Bowen ratio and eddy correlation techniques. These results highlight the fact that a thorough examination of the sensible heat flux theory is urgently needed before adequate LE_d estimates can be expected for landscapes where vegetation is sparse and soil temperatures often exceed 50° C.

An advantage of the airborne remote sensing method over conventional methods is that the spatial distribution of evaporation can be estimated over entire fields. The areal limitation of the method is determined by the distance that the ground-based micrometeorological measurements can be extrapolated. With clear sky conditions, the areal extrapolation of incoming solar radiation could extend many km with little error. Under these conditions, the spatial variations in windspeed and air temperature would probably be the limiting factors.

ALFALFA 84/85/86

In early 1984 we planted alfalfa in the "backyard" lysimeter field at the U.S. Water Conservation Laboratory in Phoenix. This year, 1986, marked the third and final year of that experiment. The three-year rotation provided a perennial experimental crop on which we could continue to develop and refine various remote sensing approaches for estimating evapotranspiration and quantifying plant water stress. It also improved the soil structure, organic content and fertility of the field plots which had been subjected to an almost continuous sequence of small grain plantings for the previous 6 years.

Measurements and methods during 1986 were similar to those employed during prior years and will be reviewed only briefly here. More detail can be obtained from past annual reports and published manuscripts.

Micrometeorological parameters were monitored throughout the experiment; 30-minute average values were recorded via an Autodata-9 data acquisition system, and an HP-9836 interface to the HP-1000 minicomputer in the laboratory. Measurements included: observations of global and diffuse solar radiation, rainfall, windspeed and direction at one location for the entire field; reflected solar radiation, net radiation, wet and dry bulb temperatures and soil temperatures at -5cm depth for 6 representative alfalfa plots; air and soil temperature profiles and soil heat flux measurements in several selected plots. Evapotranspiration data were provided by weighing lysimeters in three plots located near the center of the field.

Neutron scattering techniques were used to estimate volumetric soil moisture and plant water use in 20 cm depth increments three times per week. Radiant canopy temperatures were measured on weekdays from 1330h to 1400h (MST) using a portable infrared thermometer pointed in nadir and oblique directions. Reflectance measurements were obtained using a handheld, nadir-oriented Exotech Model 100-A radiometer equipped with MSS bandpass filters. These data were collected 3 to 5 times weekly at a time corresponding to a nominal solar zenith angle of 57°. A Barnes MMR radiometer was used to measure reflectances and canopy temperature at selected intervals during the year.

Alfalfa treatments during 1986. Alfalfa plots were harvested 7 times from January 1986 until November 1986. This compares with a total of 6 harvests in 1984 and 9 in 1985. After the first harvest in February (when all 18 plots were harvested at once), cuttings were staggered to provide canopies with different percentage ground cover and in different stages of regrowth. The field was divided into 3 blocks comprised of 6 plots and 1 lysimeter each. During the most active regrowth period from April to September, a different block was harvested every 5 to 18 days. This block rotation of harvests facilitated comparisons of evapotranspiration, canopy temperature and reflectance under partial canopy conditions with plots having a "full" canopy. Water stress was imposed at

intervals on certain plots within each block.

Less emphasis was placed on labor-intensive plant sampling procedures during 1986. Plant biomass between harvests was not measured. Total dry biomass of each plot was estimated immediately prior to the harvest of each block. As in prior years, this was done for the "target areas" located to the south of the east-west boardwalks where canopy temperature and reflectance measurements were made on a routine basis. Hedge trimmers were used to cut the above-ground portion of the plants, leaving about a 4 cm stubble. A wet weight was obtained for the entire sample which was then subsampled for moisture content. Total wet weight was adjusted by percentage moisture in the subsample to yield biomass on a dry weight basis. The remainder of the field was cut later the same day using a combination of the sickle bar on a mini-tractor and the hedge trimmers. Litter was permitted to dry for one day after which it was raked by hand and removed from the field.

Termination of the experiment. The final harvest of the alfalfa plots occurred on 25 November 1986. Micrometeorological instrumentation and wiring was removed after which the entire field was rototilled several times to a depth of 6-8 inches and irrigated. Berms of all plots were reworked and left in their existing position. All neutron access tubes were left in place in the center of each plot. Plans were drafted to install a subsurface drip irrigation system in each of the plots.

EFFECTS OF TOPOGRAPHY ON CANOPY REFLECTANCE

Every year new satellite and aircraft platforms expand our capacity to observe the earth's surface with improved temporal, spatial and spectral resolution. Some systems permit data acquisitions at different times of the day while others provide off-nadir views using wide angle or pointable sensors. Such flexibility is desirable from a resource managing standpoint because it improves the chances of capturing frequent, cloud-free images of the same spot on the ground. But the utilization of dissimilar sensors and accompanying variations in sun angle and viewing geometry also imply that sequential images are not always comparable. A further complication is introduced when the targets are located in rolling terrain. The magnitude of this problem has not been fully documented for agricultural crops. This information is essential if we are to devise strategies that minimize the influence of topography and sun angles on vegetation reflectance. When this has been realized we can make further advances in the use of remotely-sensed data for assessing evapotranspiration rates and agronomic parameters over broad regions.

One such research project evolved from cooperative research with personnel at the Istituto Di Agronomia Facolta' Di Agraria, CNR, Florence, Italy. It consisted of a field experiment to ascertain the effect of topography and sensor viewing angle on the spectral reflectance and emittance properties of agricultural crops. A

secondary objective was to transfer ground-based remote sensing technology to Italian researchers at the Institute. Funded by the Office of International Cooperation and Development (USDA), this project was conducted in central Italy during the spring of 1986.

The site chosen for this study was a university research farm in Fagna, Italy, about 35 km north of Florence where large scale experiments were underway to examine the effect of topography on growth, development and microclimatology of winter wheat. The area was typical of undulating topography in many parts of the world where small grains are grown under rainfed conditions. The remotely-sensed reflectance measurements collected during May 1986 supplemented the Italian research objectives by providing quantitative information on wheat canopy conditions over a critical crop growth period from just prior to heading until after anthesis.

Reflectance data were collected on most clear days during the first three weeks in May using a handheld Exotech radiometer equipped with spectral bandpass filters similar to the first four Thematic Mapper channels. When weather conditions permitted, measurements were taken from early in the morning until late in the afternoon. This yielded a wealth of reflectance data under a wide range of solar azimuth and zenith angles. Such ground-based diurnal observations have an experimental advantage over actual satellite data because they mimic reflectances that might be collected at other latitudes or different times of the year. However, the effects of topography and sun angles on reflectance can be isolated because the data are not confounded by growth of the plants or seasonal changes in atmospheric properties.

Reflectance data were obtained for three adjacent fields of winter wheat, representing several different slope and aspect conditions. Various soil, alfalfa, and pasture targets were measured on a less intensive basis. Three radiometer viewing angles were employed: nadir, 20°off-nadir towards the east, and 20°off-nadir towards the west. Reflectances were computed as the ratio of canopy radiances to irradiance levels in each waveband. The latter were estimated via measurements over a horizontal, 30.5 by 30.5cm calibrated halon reflectance standard.

Analysis of data collected during this experiment is continuing and was the theme of two oral presentations at the 1986 Annual American Society of Agronomy meetings and a journal manuscript submitted in 1986. Results showed that time of day, viewing angle and terrain all have important implications for interpreting remotely acquired reflectance data. Moderately sloped fields cause a bias in single band reflectance factors that is dependent upon field aspect and solar angles. Such effects must be considered when these data are used to estimate evapotranspiration or assess crop condition.

Transformation of data into multiple band vegetation indices (VIs) for assessing agronomic parameters does not eliminate this dependence on

time of day even when the canopy covers the soil completely. Depending upon the method of computation however, VIs vary in their sensitivity to topography and viewing direction. The ratio of NIR to Red reflectance factors preserves maximum information on agronomic characteristics while remaining relatively unaffected by field slope and aspect. By contrast, VIs that are computed as linear combinations of several wavebands (like Greenness) will require a correction for slope and aspect if they are to retain utility for assessing agricultural parameters in complex topography. Vegetation indices also varied in response to radiometer viewing direction, with Greenness values being highest when the radiometer is pointed towards the canopy "hot" spot and the ratio VI highest when viewing in the opposite direction.

Implications of this project suggest that topographic effects will affect data from current resource monitoring satellites, but the effect will be smallest for images acquired during the summer at low latitudes. It is clear that data collection efforts should strive for consistency in both sun and viewing angles. Sequential imagery collected at different times of the day or with different viewing directions will not be directly comparable. Atmospheric absorption, path radiance and signal quantization levels were not considered in the present study. However, information in the literature suggests that they will complicate image analysis still further.

A COMPUTER PROGRAM TO SIMPLIFY THE COMPUTATION OF THE CROP WATER STRESS INDEX

The thermal infrared region of the electromagnetic spectrum provides an estimate of the water status of plants indirectly by monitoring canopy temperatures and inferring the plants' ability to meet current evaporative demand. However, crop canopy temperatures *per se* are not sufficient to quantify plant stress when parameters like air temperature, vapor pressure and net radiation vary from day to day and over the course of the growing season. As a result a number of indices have been developed to make thermal estimates of crop stress more independent of environmental variation. Several of these indices, the Stress Degree Day (SDD), the Crop Water Stress Index (CWSI) and Temperature Difference Stress Index (TDSI) are relative measures of plant water stress developed through research on various crops at the U.S. Water Conservation Laboratory. These indices of water stress are calculated from crop canopy temperatures measured with an infrared thermometer and various meteorological parameters. The CWSI and TDSI scale observed canopy temperatures relative to minimum and maximum temperatures expected for well-watered and severely stressed canopies, respectively. Each index value varies from zero for a crop with an adequate supply of moisture to unity when stomata are completely closed and transpiration has ceased.

The computation of these indices is facilitated by a user-friendly program written in Pascal for PC-compatible microcomputers. The menu

driven program permits the user to interactively manipulate input variables and examine their effect on the resultant calculation of expected upper and lower extremes in plant temperature as well as the CWSI and TDSI. Both empirical and theoretical methods for calculation are supported. Data from actual field experiments can be entered and stored for later analysis. The program predicts a date for future irrigations based on user-defined CWSI threshold values. All documentation is provided by context sensitive help screens. A comprehensive listing of references related to the development of the temperature stress indices and their utility in the monitoring of plant stress is included on diskette. The source code is also provided for programmers who wish to modify the procedures for their own use.

The program is in the public domain and available from the authors free of charge provided a diskette is supplied with the request.

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Table 1. MAC farm data collection summary.

Key: F = field number; C = cover type (W = wheat/barley, C = cotton, A = alfalfa, S = bare soil); Q = quality of data (1 = excellent, 2 = good, 3 = poor); T = type of TM data (F = fully processed, A = partially processed)

			GROUND							AIRCRAFT		LANDSAT	
DATE	YEAR, DAY	WEATHER	MMR F C Q	EXOT/IRT F C Q	OBLIQUE IRT F C Q	PHOTOS Q	MET STATION 2 F C Q	MET STATION 1 F C Q	Bowen Ratio F C Q	EXOT/IRT Q	PHOTOS Q	TM Data T	Atmos. Data Q
18 APR 85	85,108	clear	31 W 1		22 A 1	1	21 A 2		29 S 1			P	1
4 MAY 85	85,124	light cirrus around sun	30 C 1 31 W 1			1		31 W 2	31 W 1			A	2
20 MAY 85	85,140	clear	28 C 1			1		28 C 1					
5 JUN 85	85,156	clear, cirrus along horizon	29 C 1 30 C 1			1		29 C 1	29 S 1				1
21 JUN 85	85,172	clear	30 C 1			1		30 C 1		1	1	A	2
7 JUL 85	85,188	light cirrus around sun	29 C 1 30 C 1	22 A 1 21 A 1	22 A 1	1		29 C 1		1	1		3
23 JUL 85	85,204	clear, scattered cumulus	28 C 1 29 C 1	22 A 1 21 A 1	22 A 1	1	21 A 1	29 C 1	28 C 1	1	1	P	1
8 AUG 85	85,220	clear, cirrus along horizon	31 C 1 32 S 1			1	21 A 1	31 C 1		1	1		2
24 AUG 85	85,236	clear, cirrus around sun	31 S 1	22 A 3 21 A 3	22 A 1	1	21 A 3	28 C 1	28 C 1	1	1		3
25 SEP 85	85,268	cirrus over sun	21 A 1	22 A 1 21 A 1	22 A 1	1	21 A 1	28 C 1		2	1		
11 OCT 85	85,284	clear, cumulus on horizon	13 S 1 22 A 1	22 A 1 21 A 1	22 A 3	1	21 A 1	28 C 1		2	1		1
27 OCT 85	85,300	clear, cumulus & cirrus around sun	21 A 1	22 A 1 21 A 1	22 A 1	1	21 A 1	13 S 1		1		A	1
14 DEC 85	85,348	clear	13 S 1	22 A 1 21 A 1	22 A 1	1	21 A 2	21 A 1		1	1		1
30 DEC 85	85,364	cirrus and cumulus over sun		22 A 1 21 A 1	22 A 1	1	21 A 1	21 A 1		1	1		
15 JAN 86	86,015	cirrus & cumulus around sun, clear at 10:30 AM	22 A 2	22 A 1 21 A 1	22 A 1	1		22 A 1		1	1	A	
4 MAR 86	86,063	clear	28 W 1	22 A 1 21 A 1		1	21 A 2	28 W 1		1	1		1
20 MAR 86	86,079	clear	28 W 1			1	28 W 2	28 W 1		1	1	A	1
5 APR 86	86,095	clear, cirrus on horizon	27 W 1	22 A 2 21 A 2		1	21 A 1	27 W 1	27 W 1	1	1	A	1
21 APR 86	86,111	clear	15 S 1 23 S 1	22 A 3 21 A 3		1	21 A 2	23 S 1	27 W 1	1	1	A	1
23 MAY 86	86,143	cirrus over sun	23 S 1	22 A 1 22 A 1		1	21 A 3	23 S 1		1	2		
24 JUN 86	86,175	clear, cirrus & cumulus on horizons	30 S 1 29 S 1	22 A 1 21 A 1		1	21 A 1	29 S 1	21 A 1	1	1	A	

Table 2. Daily LE (mm) estimated using the remote method with both the theoretical and empirical approaches.

	Theoretical		Empirical	
	Ground	Air	Ground	Air
Site 2				
DOY 153	3.2	3.3	4.5	3.9
154	3.4	1.9	4.0	2.2
156	2.5	1.1	4.3	2.2
Site 5				
DOY 156	2.1	1.6	2.1	1.1
Site 10				
DOY 153	5.2	6.3	6.3	6.8
154	5.5	5.4	6.4	6.6
156	5.4	4.1	6.4	6.8

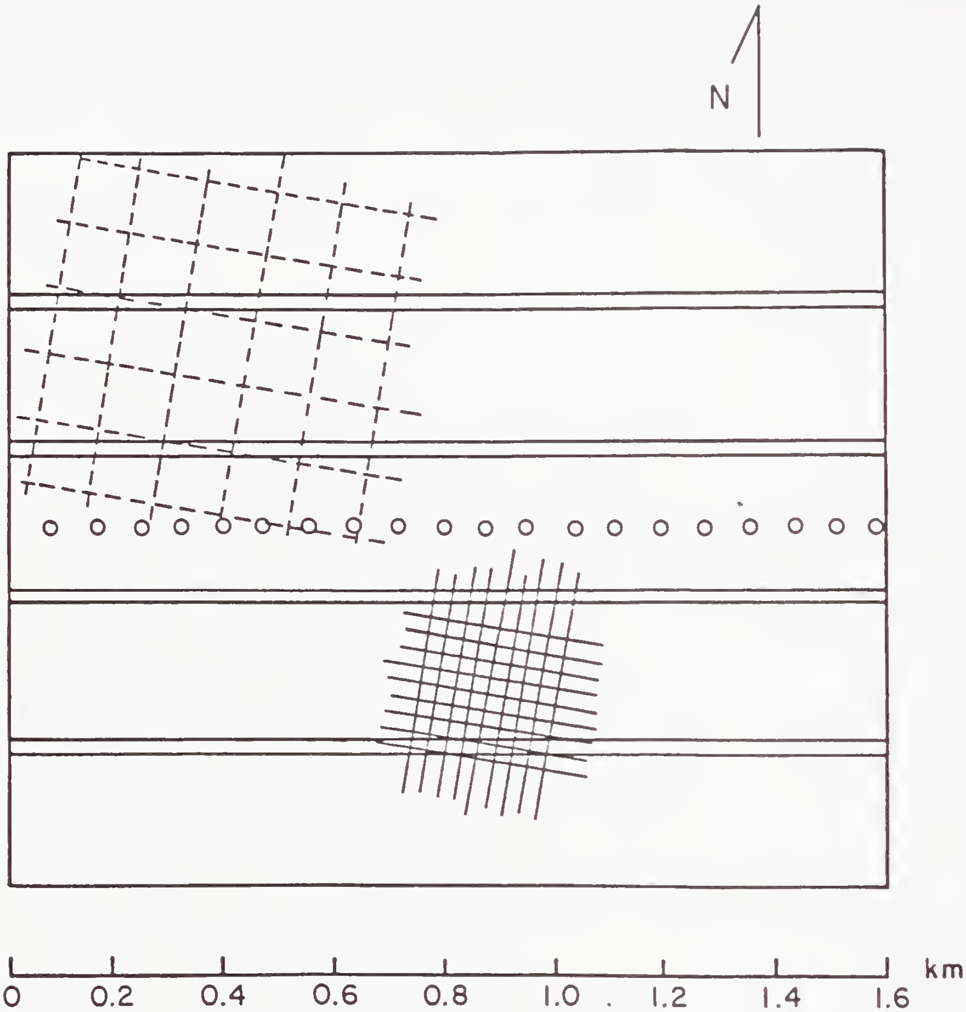

Figure 1. Comparison of resolution of airborne radiometers and Landsat TM in relation to field size at MAC farm.
Solid lines represent resoltion of TM1-TM5 and TM7.
Dashed lines represent TM6.
Circles represent resolution of the airborne Exotech and IRT.

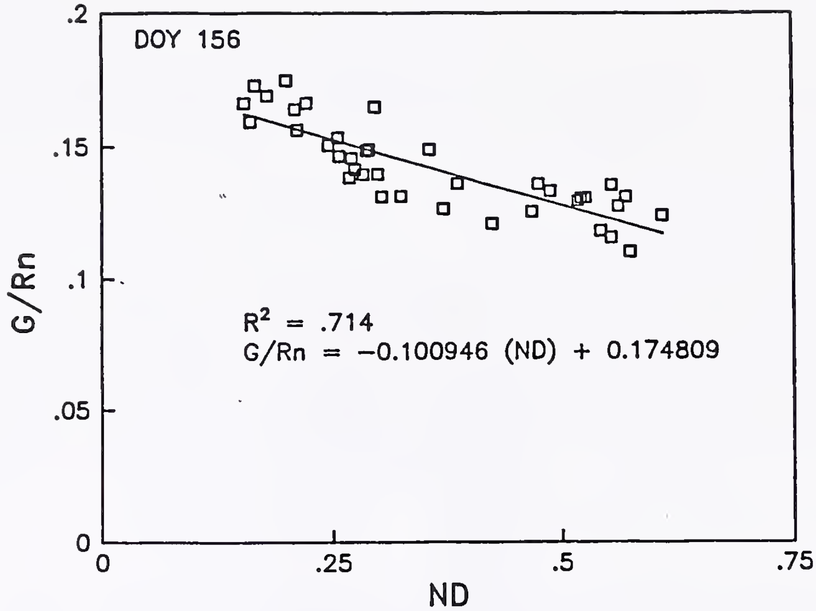

Figure 2. Relationship between soil heat flux (G), net radiation (R_n), and the normalized difference vegetation index (ND). Data are for sites 2 and 10 over a 6 hour period on DOY 156 with G measured with heat flux sensors and R_n calculated using the remote method.

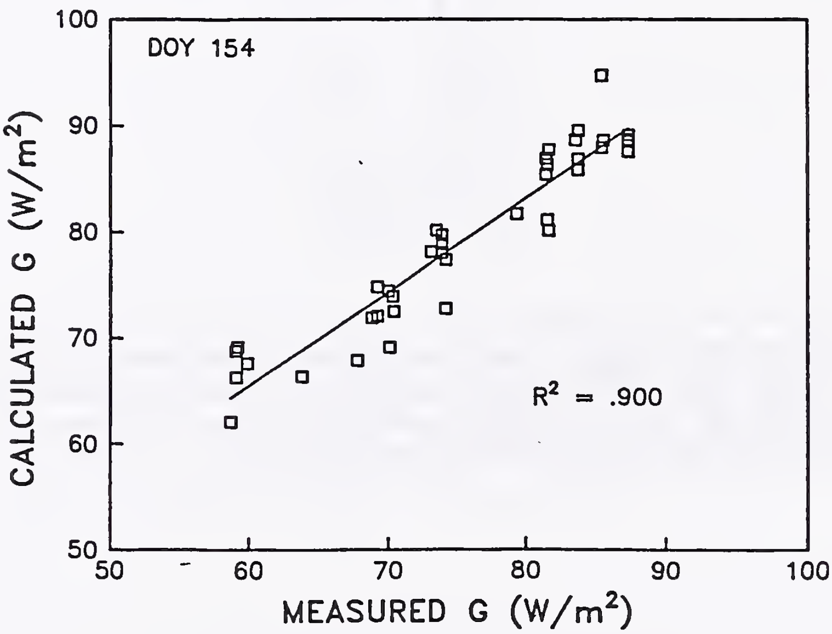

Figure 3. A comparison of calculated and measured soil heat flux values for sites 2 and 10 for DOY 154.

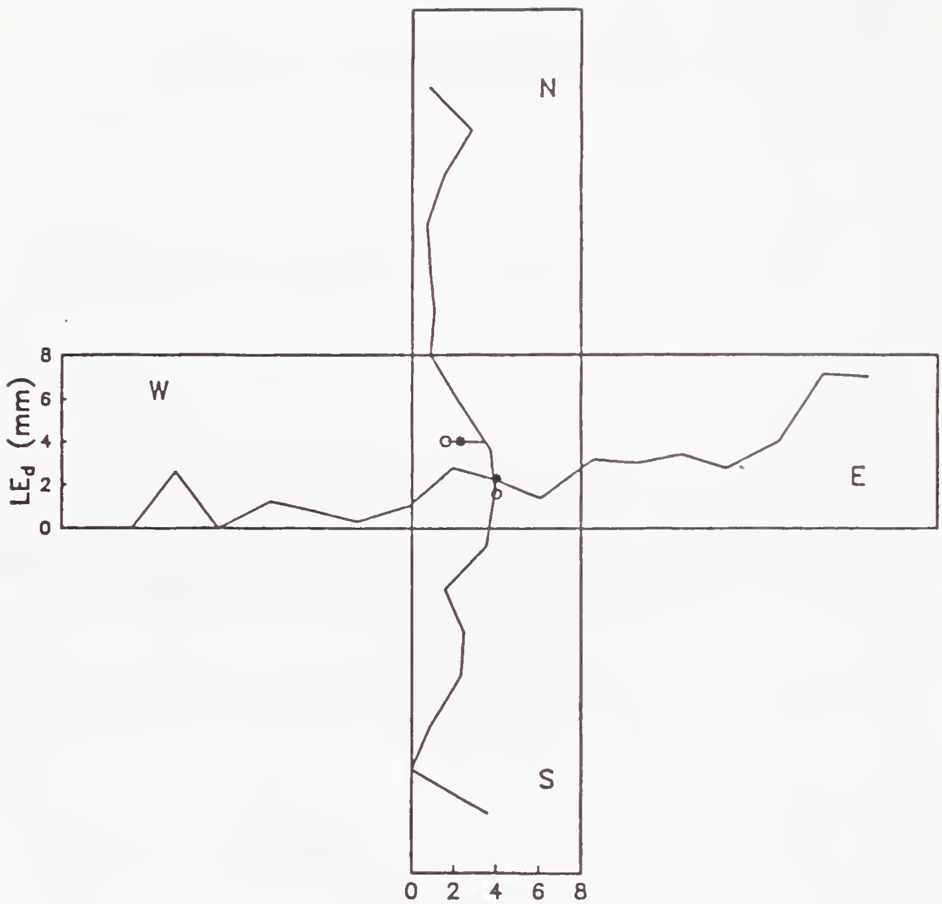

Figure 4. Estimated values of daily evaporation using the remote method along two flight lines over site 2 on DOY 156. The * and o symbols represent corresponding values of LE_d as measured with the Bowen ratio and the eddy correlation methods, respectively.

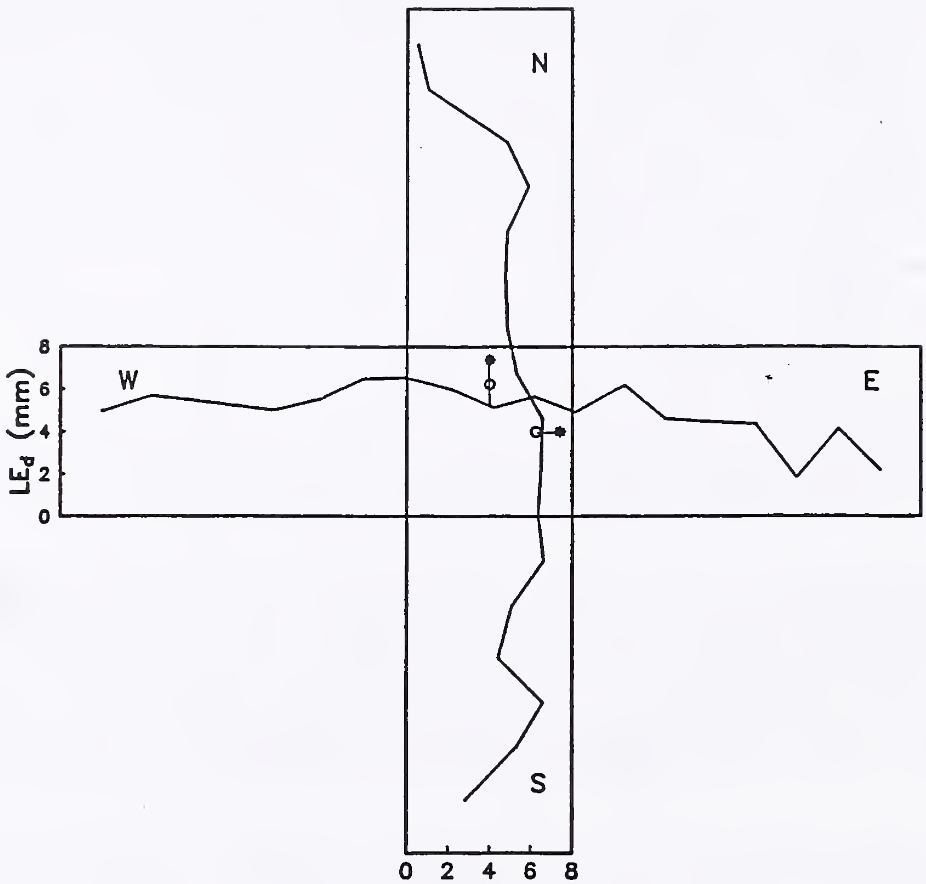

Figure 5. Estimated values of daily evaporation using the remote method along two flight lines over site 10 on DOY 156. The * and o symbols represent corresponding values of LEd as measured with the Bowen ratio and the eddy correlation methods, respectively.

TITLE: ACCELERATED HERBICIDE LEACHING RESULTING FROM PREFERENTIAL FLOW PHENOMENA AND ITS IMPLICATIONS FOR GROUND WATER CONTAMINATION

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INTRODUCTION

Recent laboratory and field evidence indicates that standard miscible displacement theory often underestimates the rates of water and chemical movement in unsaturated soils. Even with very uniform materials such as glass beads or sands, bypass flow, or the presence of "immobile" water, can be significant (DeSmedt and Wierenga, 1984; DeSmedt et al., 1986). With field soils, even those exhibiting little structure, bypass flow can have a major influence on solute distribution. For instance, Kies (1981) found pore water velocities up to a factor of 11 greater than expected based on standard miscible displacement theory in an experiment conducted on a trickle-irrigated agricultural field. Sharma and Hughes (1985) concluded that up to 50% of the water present in deep aeolian sands was not participating in miscible displacement during recharge under natural rainfall conditions. Recent tracer experiments (Bowman and Rice, 1986; Rice et al., 1986) have indicated rates of solute transport from one and one half to five times faster than predicted from traditional water balance models, under flood-irrigated agricultural conditions. This accelerated leaching has been attributed to the presence of preferential flow paths in the soil.

The purpose of the study described here was to look at this preferential flow phenomenon in more detail, and to determine its effect on the distribution of a mobile herbicide under flood-irrigated conditions. The field experiment was performed in 1985. The tracer and herbicide analyses, and interpretation of the data, were concluded in 1986. Some of the details of experimental design discussed in the 1985 annual report are also included here for completeness.

Bromacil (5-bromo-3-*sec*-butyl-6-methyluracil) is a photosynthesis inhibitor used primarily on non-cropland areas for control of annual and perennial grasses and broadleaf weeds. It also finds use for weed control in citrus orchards and pineapple plantations. It was chosen for this study primarily for its physical and chemical characteristics; bromacil is relatively non-volatile, is resistant to microbial degradation in soils, and is not strongly sorbed by most soils. Thus, it was a well-suited test compound for a several-month-long study of pesticide movement under field conditions.

MATERIALS AND METHODS

Bromacil

Analytical standard bromacil (> 99% purity) for methods development was obtained from E. I. duPont deNemours and Company, Agricultural Chemicals Department, Wilmington, Delaware 19898[1]. For field experiments, the

commercial formulation Hyvar-X (80% bromacil by weight) was used. Hyvar-X is a wettable powder. To increase the solubility of Hyvar-X for the purpose of spraying a concentrated bromacil solution on the field, Hyvar-X was dissolved in a KOH solution. The ratio of Hyvar-X to 86% KOH was 2.3:1 by weight.

Field Plot Design

The plot was established on uncropped Mohall sandy loam (fine loamy, mixed, hyperthermic Typic Haplargid) at the University of Arizona's Maricopa Agricultural Center in central Arizona. The soil had been cropped to cotton, but was bare for at least 18 months prior to the experiment. The soil exhibited significant nonuniformities with depth. The upper 1.6 m consisted of a fairly uniform sandy loam containing few coarse fragments. This texture continued to about 2.2 m, but many rock fragments of size 2 mm to 20 mm were encountered in this depth range. Below 2.2 m, streaks of carbonate-indurated material appeared within the sandy loam matrix.

The 0.62-ha plot was subdivided into 56 7.6-m by 10.7-m subplots, separated from one another by earthen berms. Neutron-probe access tubes were installed to a depth of 2.7 m in the centers of 14 of the subplots. Intact soil cores taken during access tube installation were used to calculate the bulk density for each 20-cm depth increment. The 14 subplots were chosen randomly throughout the field, with the constraint that one subplot occurred in each of 14 equal area portions of the field. These same subplots were used for tracer/herbicide additions and sampling (Fig. 1).

Experimental Procedure

Irrigation water was supplied to the field with gated pipe. Each of the 56 subplots was irrigated individually to minimize water application differences across the field. Soil water content measurements were made periodically using the neutron moisture probe. Evaporation rates from the bare soil surface were estimated by the method of Rice and Jackson (1985), using air temperature, relative humidity, soil heat flux, wind speed, and incoming solar, net, and reflected solar radiation data, collected continuously by a weather station located at the field site.

Following a 12.5-cm irrigation without chemical addition, five 7.5-cm irrigations, each labeled with a different tracer and/or bromacil, were applied to the field plot over an 11-week period. Prior to each 7.5-cm irrigation, 14 of the 56 subplots were sprayed with tracer or tracer/bromacil solution. The tracers used were 2,6-difluorobenzoic acid (2,6-DFBA), pentafluorobenzoic acid (PFBA), o-trifluoromethylbenzoic acid (o-TFMBA), m-trifluoromethyl benzoic acid (m-TFMBA), and potassium bromide (Br^-). The use of these tracers for measuring soil water fluxes has been described elsewhere (Bowman, 1984a; Bowman and Rice, 1986). The schedule of irrigations and associated chemicals is presented in Table 1. A separate tracer or tracer/herbicide formulation was prepared for each of the 14 treated

subplots. Each tracer was converted to its potassium salt and dissolved in 32L of water. This solution was sprayed on the soil by making five to six passes with a hand-held spray rig over each 7.6-m by 10.7-m subplot.

Table 1. Schedule of irrigations and tracer/herbicide additions.

Day	Date (1985)	Irrigation Amount (cm)	Tracer/Herbicide Name	Tracer/Herbicide Rate ($g\ m^{-2}$)
0	22 March	12.5	-	-
13	4 April	7.5	2,6-DFBA	2.34
25	16 April	7.5	PFBA Hyvar-X	2.99 3.94
40	1 May	7.5	o-TFMBA	1.49
54	15 May	7.5	m-TFMBA	1.49
76	6 June	7.5	Br^-	12.4
81-84	11-14 June	Soil core samples taken.		

Soil cores from all 14 treated subplots were obtained during a four-day period commencing 56 days after the PFBA/Hyvar-X addition. The cores were taken using Veihmeyer tubes equipped with 2.0-cm I.D. tips. Seven randomly-positioned cores, in 30-cm increments to a depth of 2.7 m, were taken in each of the 14 subplots which had received all five tracers and Hyvar-X. Thus, a total of 98 points were sampled (Fig. 1). Each 30-cm soil core was placed in a Ziploc[1] bag and the bag put on ice in an ice chest to minimize bromacil degradation after sampling. Upon return to the laboratory, all samples were frozen until analysis.

Chemical Analyses

For tracer analyses, a 20-g subsample of each 30-cm core at field moisture content was extracted with 10-ml of water by shaking for 20 minutes in a 50 ml polypropylene centrifuge tube. After centrifugation and filtering, the tracers were quantified using an HPLC technique described earlier (Bowman, 1984b). A separate 10-g subsample was taken at the same time for gravimetric moisture content determination. A final separate 10-g subsample was shaken with 10 ml of methanol for 20 minutes, for total extraction of bromacil. Bromacil content in the methanol extracts was measured via HPLC, using an octadecylsilane column and a methanol/water mobile phase, with ultraviolet detection at 280 nm.

RESULTS AND DISCUSSION

The following discussion concerns the distribution and recovery of bromacil and the tracer PFBA. Discussion and interpretation of the data on

the other four tracers used in this experiment were discussed in the 1985 Annual Report.

Bromacil Recovery

Based upon the amount of bromacil added to each 7.6-m by 10.7-m plot (Table 1), and the cross sectional area of the sampling device (3.14 cm^2), a total of 989 μg of bromacil could be expected to be recovered from the entire column of soil at each core sampling location in the absence of any chemical or microbial degradation of the herbicide. Total bromacil recovered at each location was calculated by summing the individual bromacil recoveries at each sampling depth, making use of the bromacil concentra-tion in the methanol extract, the gravimetric water contents and the soil bulk density. Bromacil recovery, expressed as a fraction of the amount applied, averaged 0.89 for the 98 sample locations, with a range of 0.34 to 2.34, and a coefficient of variation of 0.45.

The wide range of the recoveries across the 98 sampling locations was likely due in part to uneven distribution of the bromacil when originally sprayed on the soil surface. The mean recovery of 0.89, however, should have been a good measure of the average persistence (resistance to chemical and microbial degradation) under the given experimental conditions. Using the mean recovery and given that the bromacil was added to the soil 57 days before sampling (Table 1), the mean half-life ($t_{1/2}$) for bromacil in the upper 2.7 m of this soil is calculated to be 339 days. This value is consistent with bromacil half lives measured by other workers. Rao and Davidson (1980) reported a mean field $t_{1/2}$ for bromacil of 349 days. Gardiner et al. (1969) found a field $t_{1/2}$ of 150 to 180 days, and a laboratory value of 150 days. Gerstl and Yaron (1983) reported laboratory-determined $t_{1/2}$ values for two different soils under different temperature and moisture conditions. Their values ranged from 14 days at elevated temperatures (50°C) to almost 1500 days at 25°C and low initial moisture content. They determined a mean $t_{1/2}$ of 590 days for the two soils at 25° and a moisture content at "field capacity."

Tracer Movement

The distribution of PFBA peak maxima over the sampled depth intervals is shown in Fig. 2. After 57 days, most of the PFBA was found in the 90-120-cm sampling interval. Along with the histogram, the normal distribution calculated from the mean and variance of the tracer peak distribution is also presented in Fig. 2. The distribution is well-described by the normal curve. This finding contrasts with those of other workers (Biggar and Nielsen, 1976; van de Pol et al., 1977; Jury et al., 1982) who have found log-normally distributed velocity distributions for tracer transport in agricultural fields.

For each sampling location, the downward rate of water movement was calculated from the PFBA distribution versus depth. The velocity was determined by fitting the one-dimensional convection-dispersion equation to the data (Bowman and Rice, 1986)

$$\frac{\partial C_s}{\partial t} = D_s \frac{\partial^2 C_s}{\partial x^2} - v_s \frac{\partial C_s}{\partial x} \tag{1}$$

where C_s is the PFBA concentration, t is time, x is the sampling depth, D_s is the dispersion coefficient of the tracer, and v_s is the mean velocity of the tracer. Estimates of D_s and v_s were obtained using the least-squares optimization procedure described by Parker and van Genuchten (1984), assuming resident concentration values for PFBA. Although this solution of Eq. (1) is based upon steady-state water flow conditions, it yields reasonable estimates of v_s under intermittent water application, as discussed by Bowman and Rice (1986). From the curve-fitting procedure, a mean PFBA velocity of 1.67 cm d^{-1} was calculated, with a coefficient of variation of 0.48.

An estimate of the mean pore water velocity, v_o, was obtained from the measurements of net water input and mean profile water content using the relationship

$$v_o = q/\Theta \tag{2}$$

where q is the Darcy velocity and Θ is the volumetric water content. Equation (2) is traditionally used to estimate water flow velocities in homogeneous porous media and is often assumed to be valid for both saturated and unsaturated water flow under field conditions. Application of Eq. (2) implicitly assumes that all stored water participates in miscible displacement, and that $v_o = v_s$.

The mean Darcy velocity during the course of the experiment, calculated from the amount of water applied minus the soil evaporation, was 0.16 cm d^{-1}. Using the measured average profile value of Θ of 0.242, the mean pore water velocity, v_o, was calculated to be 0.66 cm d^{-1}. The ratio of the measured tracer velocity, v_s, to the mean pore water velocity, v_o, was thus 1.67/0.66, or 2.5:1. This v_s:v_o ratio is consistent with results from an earlier transport experiment in this same field which yielded ratios ranging from 2:1 to 5:1 (Rice et al., 1986).

The large discrepancy between v_s and v_o indicates that about 60% of the stored profile water was not participating actively in miscible displacement in this field experiment. As a result, surface-applied water was moving downward at a rate about two and one-half times faster than predicted from Eq. (2) and standard miscible displacement theory. The implications of this accelerated water movement on ground water recharge are discussed by Bowman and Rice (1986) and Rice et al. (1986).

Bromacil Movement

The distribution of bromacil peak maxima is shown in Fig. 3. On the average, the bromacil peak was found in the 30- 60-cm depth interval. As with PFBA, the bromacil peak distribution was well described by a normal curve. This curve is also shown in Fig. 3.

As a representative example, the bromacil and PFBA distributions for the seven sampling locations in one subplot are presented in Fig. 4. Much variability was noted both in the peak position and peak shape for tracer and herbicide among locations. The relative peak positions of tracer and herbicide were also quite variable. The retardation of bromacil, due to its adsorption by the soil as it leaches downward, is clearly indicated in Fig. 4.

Figure 4 illustrates the range in behavior seen in PFBA and bromacil movement in the experimental field. For sampling holes 1, 3, 4, and 5, PFBA and bromacil show roughly the same amount of dispersion (as indicated by the similar peak shapes) and mass recoveries. For holes 2 and 6, the degrees of dispersion are markedly different for the tracer and herbicide. In hole 2, the bromacil recovery actually is higher than that for the conservative tracer, indicating possible non-uniform application of the two compounds and/or different flow paths as tracer and herbicide moved downward through the soil.

Hole 7 showed very high concentrations of both bromacil and PFBA near the soil surface. The peak concentration of bromacil was greater than 14 $\mu g\ cm^{-3}$, in the 0- 30-cm sampling interval, while the PFBA peak was in the 30- 60-cm sampling interval. Both of these peaks are off scale in Fig. 4.

The solid lines in Fig. 4 represent the fitted curves for PFBA based upon Eq. (1). The dashed curves are the fitted distributions for bromacil based upon

$$R_b \frac{\partial C_b}{\partial t} = D_b \frac{\partial^2 C_b}{\partial x} - v_s \frac{\partial C_b}{\partial x} \qquad (3)$$

where C_b is the bromacil concentration, and where R_b and D_b are the retardation factor and the dispersion coefficient for bromacil, respectively. R_b is a measure of the mobility of a sorbed chemical relative to an unretained tracer. Values of R_b for 85 of the sampling locations were determined by fitting Eq. (3) to the concentration/depth data, again using the algorithm provided by Parker and van Genuchten (1984), with the value of v_s fixed at the corresponding value for PFBA for the same sampling location. Retardation factors for 13 of the sampling locations could not be accurately determined due to poor bromacil PFBA and bromacil(0-30 peakshallowest maximathe in distributions or to the occurance of bothcm) sampling increment.

The mean R_b value determined in this manner was 1.79, with a coefficient of variation of 0.30. R_b values ranged from a minimum of 0.83 (i.e., bromacil moved downward 1.2 times as fast as the tracer), to a maximum of 4.90 (i.e., bromacil moved only 0.20 times as fast as the tracer).

Referring again to Fig. 4, the effects of averaging data from the seven individual sampling locations in one subplot can be seen in the curves labeled "Average." Due primarily to the large concentration of bromacil

at the surface in hole 7, the "average" retardation factor is 2.9, even though the retardation factors actually measured for holes 1 through 7 ranged between 1.5 and 2. Thus, compositing the samples prior to bromacil and PFBA chemical analysis would have resulted in significantly overestimating the retardation factor for this subplot.

CONCLUSIONS

The downward rate of water movement determined by tracer measurements was about 2.5 faster than would have been predicted by a traditional water balance-water content approach to miscible displacement. This rapid penetration of downward-percolating water was apparently due to the presence of preferential flow paths in the soil matrix. These preferential pathways excluded a significant portion of the mobile water from mixing with water stored in the soil profile.

The retardation of bromacil relative to the unretained tracer PFBA had a mean value of 1.8, indicating that sorption/desorption processes limit the mobility of this herbicide to about half that of the percolating water. But since bypass flow accelerated the movement of water by a factor of 2.5, bromacil moved downward about 40% faster than expected for an unretained chemical under piston-flow type water movement. Under the bypass flow conditions encountered here, the moderately mobile bromacil was converted into an "ultra-mobile" solute.

It should be emphasized that the soil in the experimental field was essentially structureless, and showed no evidence of wormholes, rootholes, cracks, or other physical characteristics usually associated with macropore flow. As with the aeolian sands described by Sharma and Hughes (1985) wherein bypass flow on the order of 50% was measured, the prefer-ential flow paths must occur on a microscopic scale. This suggests that such bypass flow phenomena may be much more common than generally recognized, and in fact may be the rule rather than the exception for solute movement under natural conditions.

The accelerated vertical movement of sorbing chemicals due to bypass flow has several implications besides the obvious one of speeding chemical transport to ground water. The processes which degrade and detoxify potentially harmful organic compounds on their inevitable journey from the soil surface to ground water are generally most active near the soil surface. Microbial degradation of pesticides and other organics is most rapid and efficient in the aerated, nutrient-rich root zone. Sorption of organic pollutants is generally greater by the high-surface area, organic rich topsoil than by subsurface deposits and rock. Near-surface soil properties cause the greatest attenuation and dissipation of downward-moving organic chemicals. If preferential flow allows a large fraction of applied pesticides to move relatively unimpeded beyond the active soil layer, the potential for transport through the vadose zone and to ground water is substantially increased.

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R. S. Bowman, R. C. Rice, G. C. Auer, and J. B. Miller

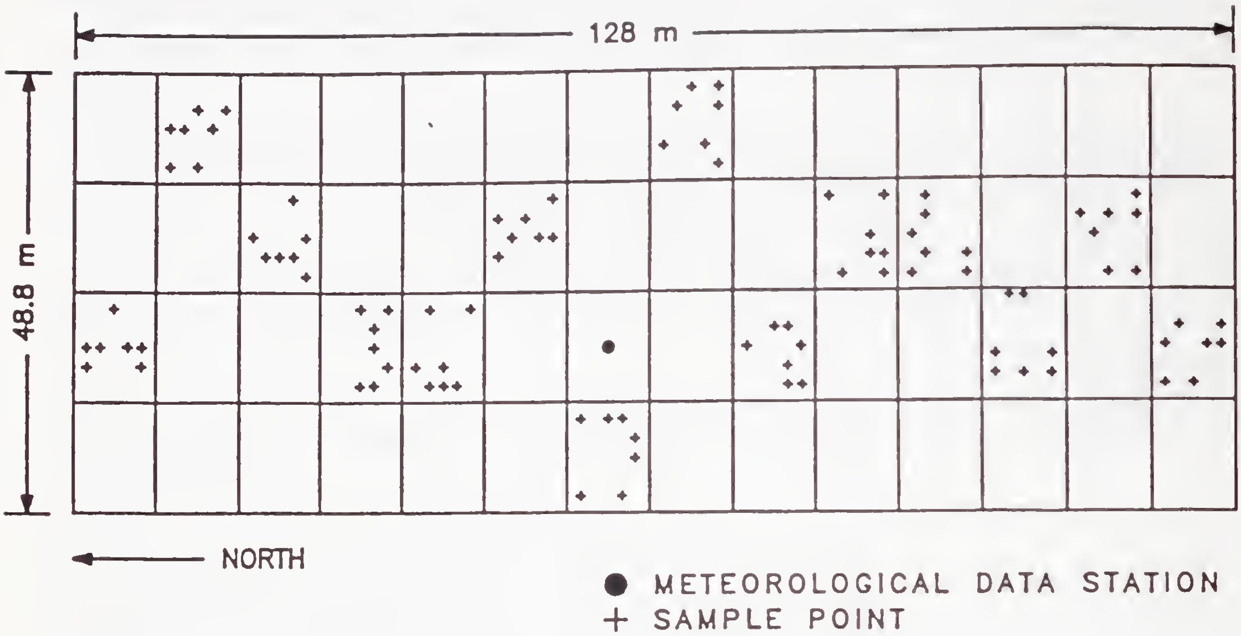

Figure 1. Schematic diagram of the experimental field, showing the locations of the weather station and the core samples.

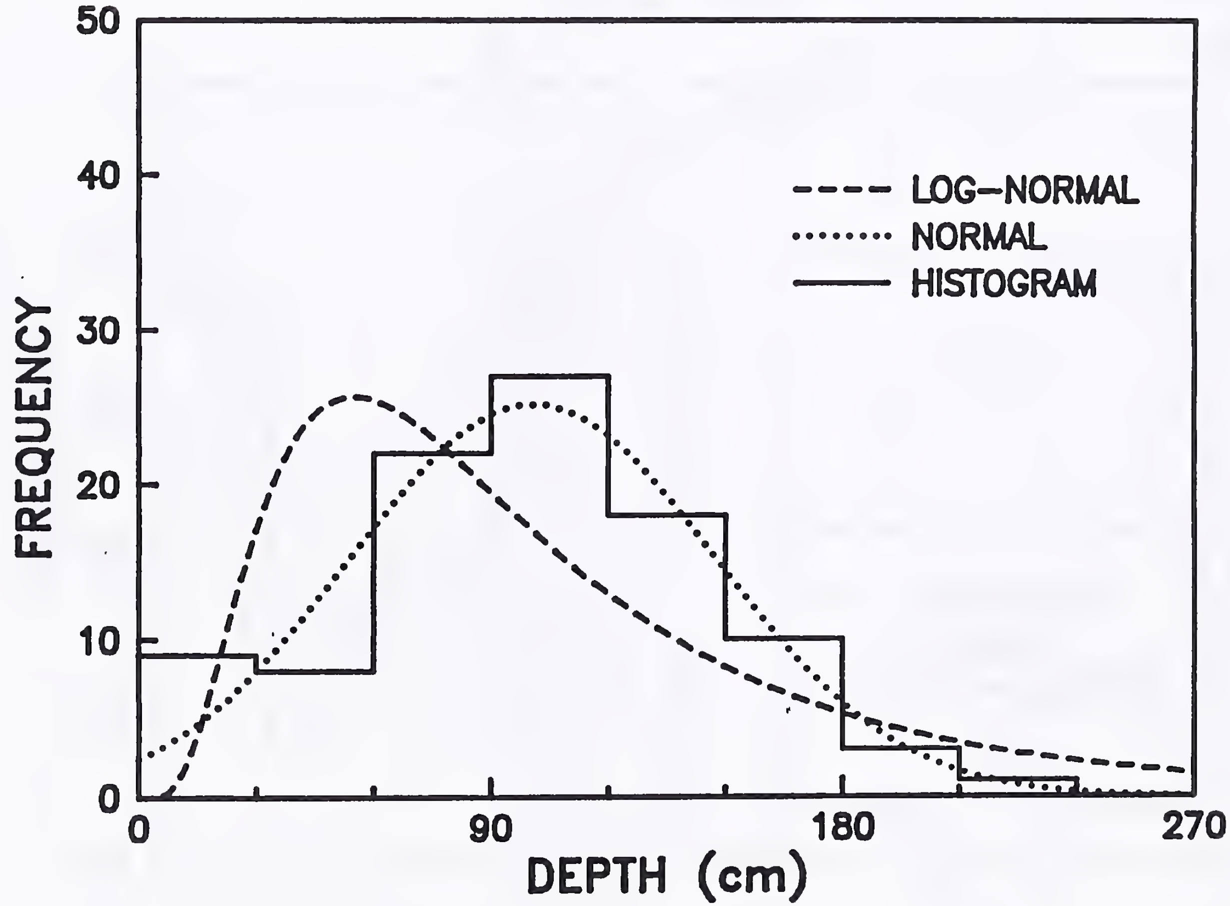

Figure 2. Distribution of PFBA peak maxima as a function of depth. The histogram represents the measured data.

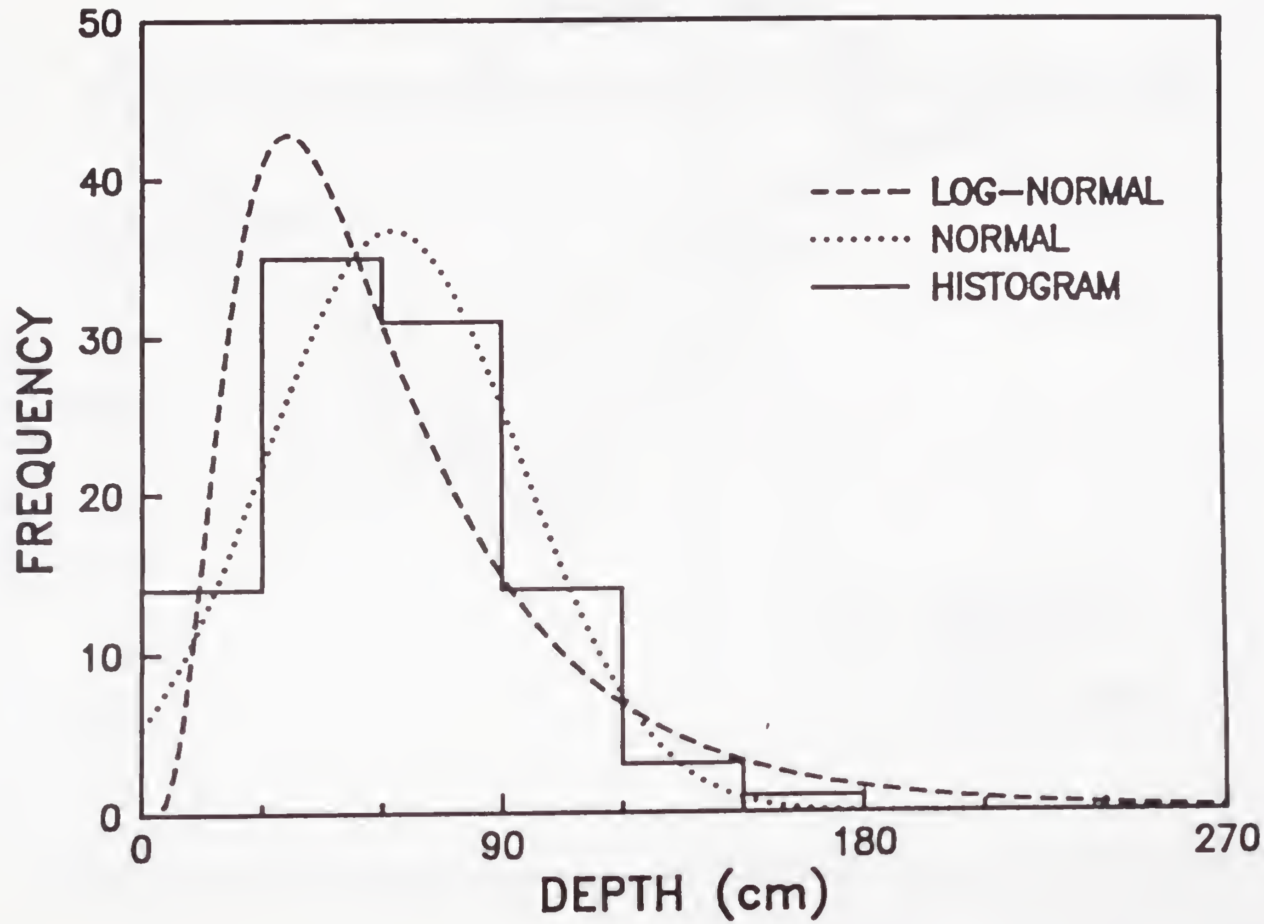

Figure 3. Distribution of bromacil peak maxima as a function of depth. The histogram represents the measured data.

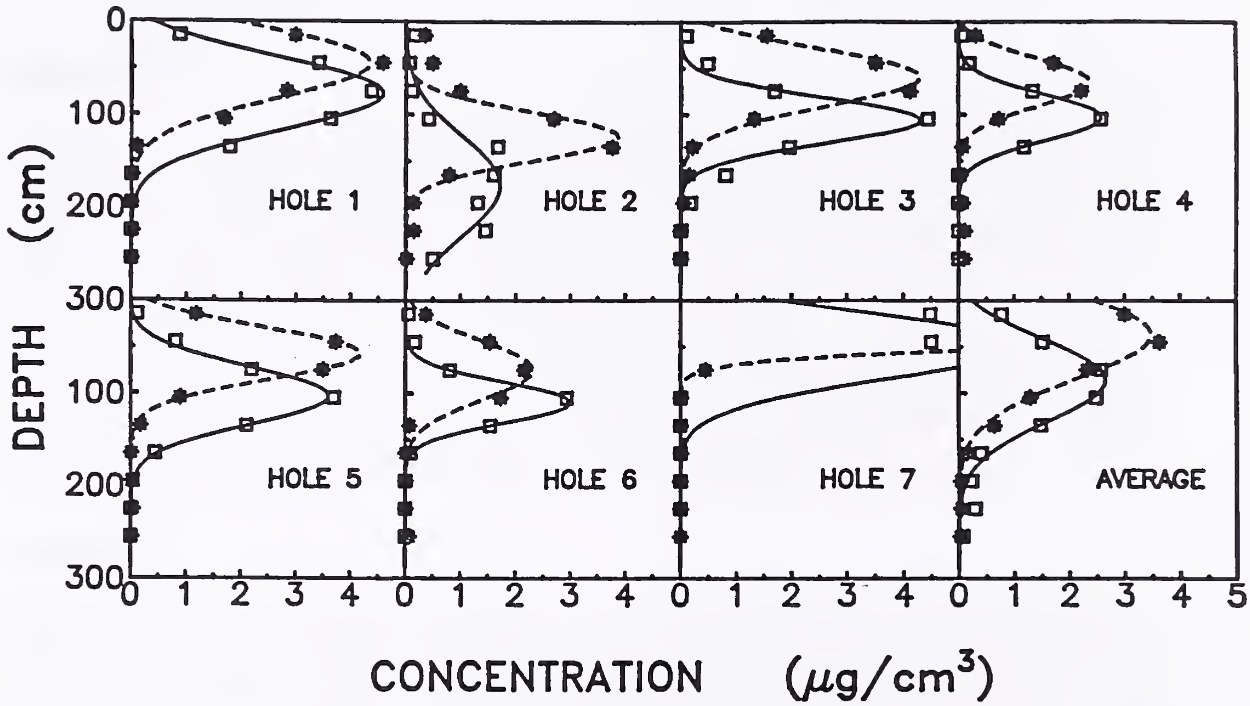

Figure 4. PFBA and bromacil distributions for subplot 7. The squares and asterisks represent measured concentrations for PFBA and bromacil, respectively. The solid lines are the fitted curves for PFBA based on Eq. (1); the dashed lines are the fitted curves for bromacil based on Eq. (3).

TITLE: BASELINE STUDY OF SALT DISTRIBUTION IN THE DEEP VADOSE ZONE

SPC: 1.3.02.1.a
1.1.02.1.c

CRIS WORK UNIT: 5422-20790-005

INTRODUCTION

More information on the quality of deep percolation water from irrigated fields is needed to accurately assess the effect of irrigation on groundwater quality. More and more observations of nitrate and pesticide contamination of the groundwater are being reported. In many areas where the water table is deep or is presently decreasing faster than the downward movement of the deep percolation water, contamination of the groundwater may not be observed for several years. The quality of the deep percolation water can be obtained by looking at the water in the vadose zone. A number of dry wells are presently being installed in the Phoenix area to rapidly dispose of urban runoff. The chemical composition of the dissolved salts in the vadose zone was determined from soil samples taken during the construction of a number of dry wells.

PROCEDURE

Soil samples of the vadose zone were taken during the construction of dry wells. The dry well consists of a 1- to 2-m diameter hole drilled 15 to 40 m into the soil, usually until a sandy layer is reached. The holes were drilled using a clam bucket type auger with each bucket removing about 30 cm of soil. A sample was taken from each bucket as it was brought to the surface. One sample was used for water content and another was taken for laboratory analysis of dissolved salts. A total of nine dry wells were sampled. Six of the wells were located in recently irrigated areas, two in non-irrigated areas and one in a runoff area from an existing parking lot. The depth ranged from 16 to 37 m. The location, depth, depth to sand layer, and average water content of the different sites are shown in Table 1. The chemical analysis was performed on a 1:1 soil extract for sites 1 through 5, and on a saturated extract on sites 6 to 9. Sites 8 and 9 were sampled every third bucket while all of the others were sampled every bucket. The cations sodium, magnesium, calcium, and potassium were determined by atomic absorption. Chloride was determined by the automated ferricanid method, sulfate by the automated methylthymol blue method and nitrate by the automated hydrazine sulfate reduction method. Bicarbonate was determined by acid titration. All of the alkalinity was considered bicarbonate because the pH was below 8.2 in all samples. Sulfate was not determined on sites 8 and 9 and bicarbonate and potassium were not determined on sites 6 through 9. All concentrations are reported relative to the field water content of the sample. Water contents are reported on gravimetric basis.

RESULTS

The concentration of the cations, anions, water content, and electrical conductivity, EC, are shown with depth for each site in Figures 1 to 3.

The concentrations are in millimols charge per liter, mmol(±)/L. The relative concentration of the different ions is expressed as specific ion concentration divided by the total ion concentration as shown in Figures 4 to 6. The ratio of cations to anions is also shown in Figures 4 to 6. The ion balance is reasonable for sites 1 to 5. Sulfate and HCO_3^- analyses were missing from sites 6-9.

Non-Irrigated Site

At the non-irrigated site, the water contents ranged from 5 to 15% with an average of 10.7%. The EC was a maximum of 20 to 25 dS/m at 4 to 5 meters and then decreased to 1 to 2 dS/m after 15 m. Sodium comprises 75 to 95% of a total cation in the top ten meters and then decreases to about 50% after 35m. Calcium and magnesium concentrations remain relatively constant below 10m but the percentage increases due to the decrease in sodium. In the zone of high salinity, between 2 and 7m, sulfate and chloride (and in one well, nitrate) were the predominant anions. Below 25m the chloride concentration decreases to 0 or near 0 values. Bicarbonate was relatively constant below 5m resulting in an increase of the total anion concentration from 10% at 5m to 90% at 35m in depth.

The average total dissolved salts, TDS below 15m was 1000 mg/l. Historical water quality data indicates that the TDS of the groundwater in the area of sites 1 and 2 was 200 to 500 mg/l and was predominantly a Na_2CO_3 or $NaHCO_3$ type which is characteristic of the soil derived from granitic and metamorphic rocks (Smith, 1982). While the TDS of the vadose zone is somewhat higher than the historical data, the relatively high bicarbonate and sodium content indicate that the salt originates from historical water.

Irrigated Sites

The irrigated sites will be discussed in two groups with sites 4 - 8 in one group and site 3 in the other. In sites 4 - 8 the water content was between 5 and 10% at the surface and then increased with depth. Average water content in the profile ranged between 18 and 25% below 2m. For all but site 5, the water content decreased when sand was reached. The EC was between 3 and 7 dS/m except for the top 2m in site 5 which was up to 25 dS/m. The C was relatively was relatively constant below 7m. Sodium is the major cation comprising between 75 and 100% of the total. Magnesium and calcium were next, in that order. Chloride was the predominant anion for the most part but never comprised more than 75% of the total. Sulfate and bicarbonate concentrations were between 10 and 50% of the total. The TDS of the irrigation water applied to the area averaged 560 mg/l and was predominantly sodium chloride in nature (Smith, 1982). While the nitrate content was less than 5% of the total, concentrations of 45 mg/l or more were observed in 70% of the samples. The average nitrate concentration for the sites 4 - 8 was 100 mg/l. The total N in the profile was 0.14 kg/m^2 or 1420 kg/ha. Assuming nitrogen applications of 300 kg/ha per year and 20% loss due to leaching, the NO_3^- in the profile represents about 24 years of nitrogen application.

Irrigation efficiency, E_i, can be calculated from the salinity of the irrigation and deep percolation water as

$$E_i = 100 (1 - C_i/Cdp)$$

where C_i equals concentration of irrigation water and C_{dp} equals concentration of deep percolation water (Bouwer, 1980). The average EC of the five sites is 4.05 dS/m or 2590 mg/l of salt concentration for the deep percolation concentration. Using the average irrigation water concentration of 560 mg/l the irrigation efficiency for the five sites was 78%.

The total annual nitrogen load to the groundwater from the irrigated area can now be estimated. If we assume an irrigated area of 72,000 ha and an average application of 1.5 m, the deep percolation amount would be 0.33 m. The average N concentration of the deep percolation water is 24 mg/l. The total nitrogen load for the groundwater then would be 5.7 X 10^6 kg/yr. About 26% of the applied nitrogen would be lost in the deep percolation water.

At site 3, the salt distribution was similar to the other irrigated sites from the surface to 8 m and below 20 m. From 8 to 20 m, the EC ranged from 10 to almost 30 dS/m which is three to ten times higher than above or below that depth. Nitrate was the major anion comprising over 90% of the total. Chloride, sulfate and bicarbonate were relatively constant throughout the entire depth. Sodium, calcium, and magnesium all increased to make up the ion balance. Because the cation:anion ratio is close to 1 in this interval, the increase in nitrate was considered real and attributed to excess fertilizer application. The increase in calcium and magnesium may be attributed to the release from the soil complex. Nitrogen fertilizer is usually applied either as anhydrous ammonia or urea. When the ammonia is nitrified, acid is released to the soil which would release calcium or magnesium from the soil complex. The higher magnesium and calcium content would then exchange some sodium from the soil resulting in increases in all three ions. The total amount of nitrogen in the profile would be on the order of 10^5 kg/ha or 10 kg/m^2. At application rates of 300 kg/ha/yr the nitrogen in the profile of this particular site represents a 333 year supply of nitrogen. The high nitrate concentration at this site is undoubtedly due to a spill, not over application to the entire field. The site was located at the lower end of the field adjacent to the intersection of two roads. It is possible that the fertilizer spreading equipment was loaded at that point, with some spillage occurring at each application.

Rainfall Runoff Site

The dry well at site 9 was located at the lower end of a parking lot. Previous to the parking lot construction, the lot was vacant for several years. Rain water draining from the parking lot was the only source of water for the past four years. The soil was a fairly uniform sandy loam to a depth of 20 m where a bedrock layer was hit. The average water

content was 14.3%. The average EC was 1.2 dS/m which was about 3.4 times less than the irrigated sites. The order of cation concentration percentages was calcium, magnesium and sodium. Potassium was not determined; however, its concentration is assumed to be very low. Sulfate and bicarbonate were not determined at this site because of the small sample size obtained from the saturated extract. For ion balance, however, sulfate and bicarbonate would have to comprise 80 to 90% of the total anions. The average nitrate concentration was 24 mg/l and was probably picked up from the parking lot.

SUMMARY AND CONCLUSIONS

A baseline study of salt distribution in the deep vadose zone was conducted. Samples of the vadose zone were collected during the construction of dry wells in the Phoenix area. The dry wells are used for disposal of urban runoff. Sites were located in irrigated, non-irrigated, and urban runoff areas. The salt distribution from the three different regimes yielded three different water qualities. The non-irrigated area exhibited a high salinity zone in the top ten meters and reached a peak at 3 to 4 m in depth. Sodium was the predominant cation near the surface but decreased with depth. Chloride, sulfate, and nitrate were similar in concentration in the upper profile but decreased with depth. The bicarbonate content remained fairly constant with depth but became the predominant anion below 15 m as the other anions decreased in concentration. Magnesium and sodium contents were about equal at the lower depths. The ion distribution in the lower vadose zone is similar to that of the historical groundwater in the area. The salt increase near the surface is probably due to concentration of the salts as a result of evaporation over a number of years.

Under irrigation, the soil water is a sodium chloride type with sodium comprising almost 80% of the cations and chloride 51% of the anions. The quality is similar but more concentrated than the applied irrigation water. While nitrate comprises only 4% of the total, the average concentration is 100 mg/l which is more than double the drinking water standard. Nitrogen loss to deep percolation was about 26% if a 300 kg/ha nitrogen application is assumed. An irrigation efficiency of 78% was calculated from the average salt concentration of the vadose zone and the applied irrigation water.

Nitrate levels were very high at one irrigated site. The average concentration in a 16 m depth interval was 10,000 mg/l with a maximum of 24,000 mg/l. This would represent a 333 year supply of nitrogen at 300 kg/ha. The high concentration was undoubtedly due to a spill at the site rather than over-application to the entire field. The soil water at the urban runoff site was calcium bicarbonate or calcium sulfate type. The total salt concentration of 770 mg/l is about 3.4 times less than that from the irrigated sites, and similar to the groundwater before large scale irrigation in the area.

PERSONNEL

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Table 1. Dry Well Information

Site	Location	Depth m	Depth to Sand m	Average Gravimetric Water Content (%)
1	Non Irrigated	34.4	___ 1/	11.3
2	Non Irrigated	36.9	___ 1/	10.1
3	Irrigated	25.6	21	18.4
4	Irrigated	20.1	19	18.2
5	Irrigated	21.3	19	24.9
6	Irrigated	25.3	19	23.7
7	Irrigated	24.4	17	22.5
8	Irrigated	15.8	12	18.0
9	Urban Runoff	20.1	20.1 2/	14.3

1/ Sand not reached
2/ Bottom of well at rock formation

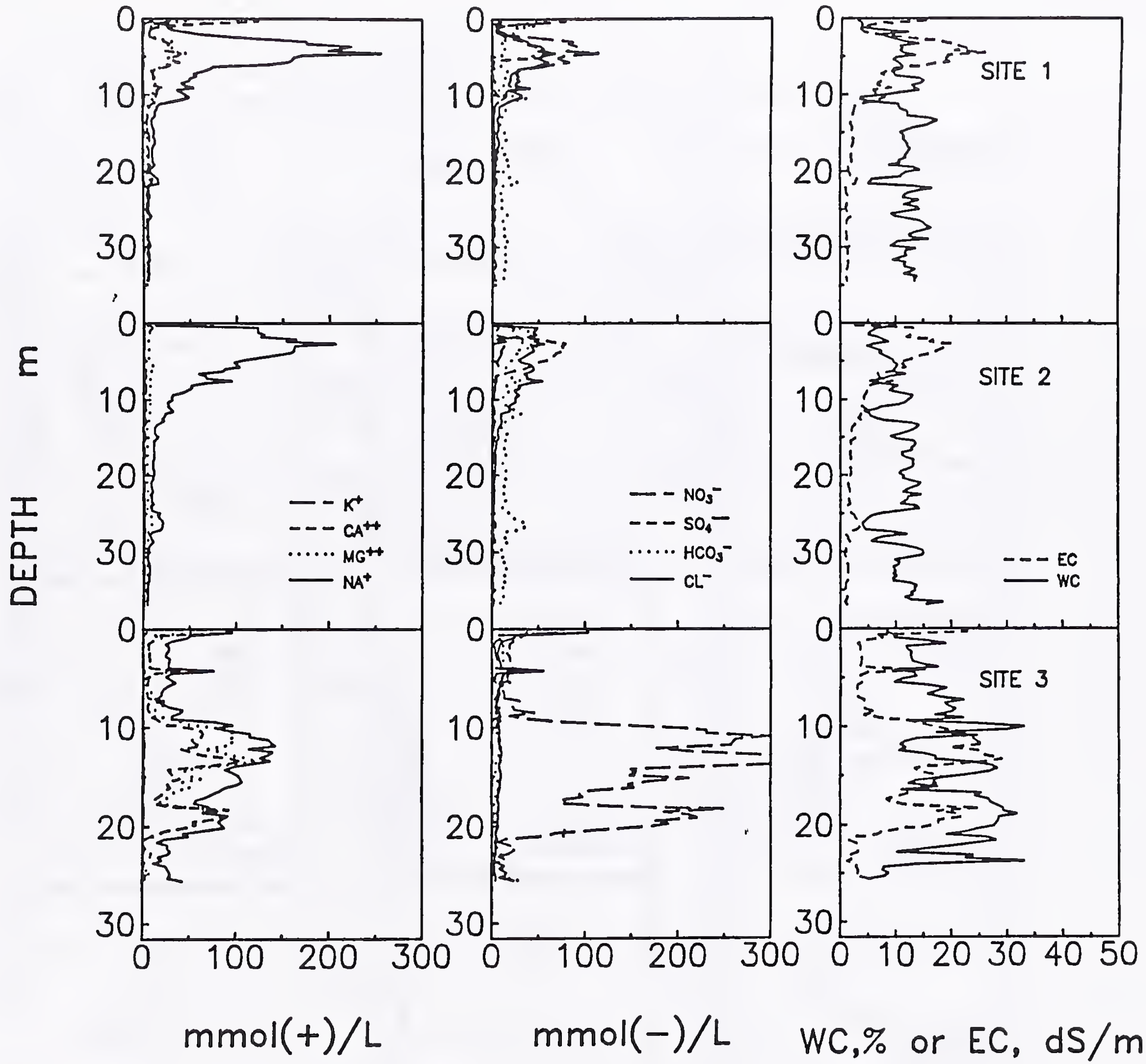

Figure 1. Cation, anion, water content, and electrical conductivity distribution with depth for sites 1, 2, and 3.

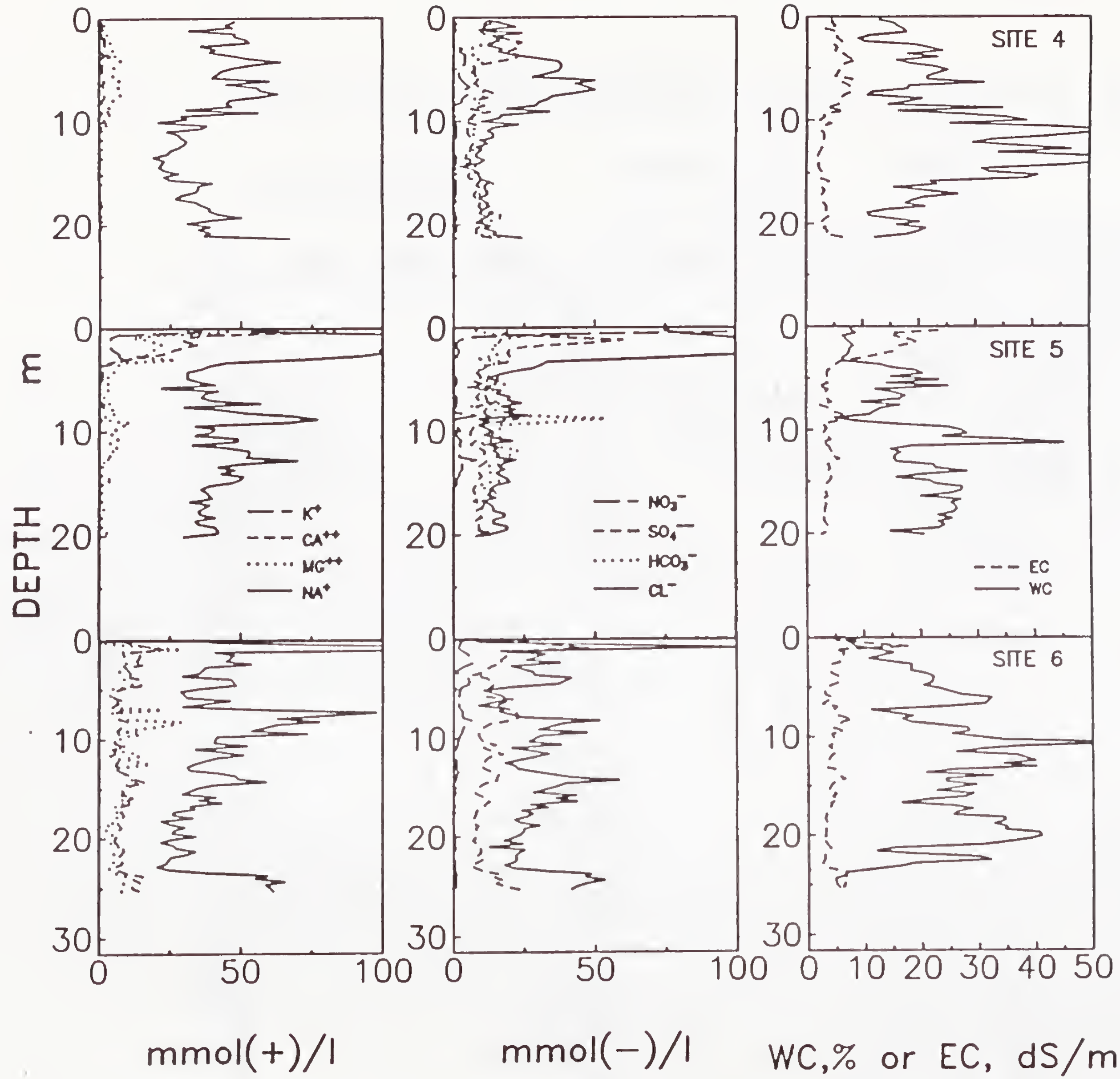

Figure 2. Cation, anion, water content, and electrical conductivity distribution with depth for sites 4, 5, and 6.

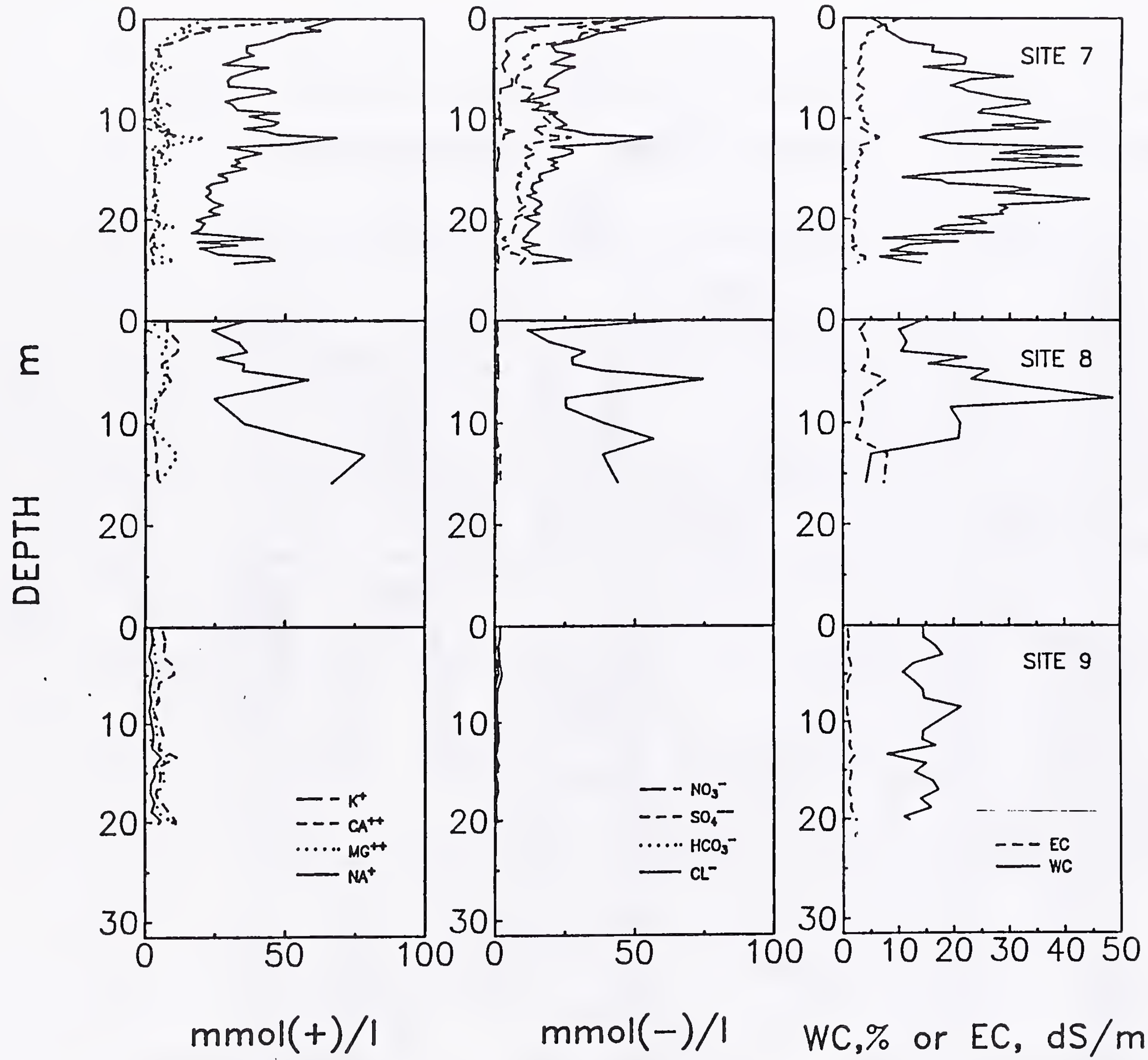

Figure 3. Cation, anion, water content, and electrical conductivity distribution with depth for sites 7, 8, and 9.

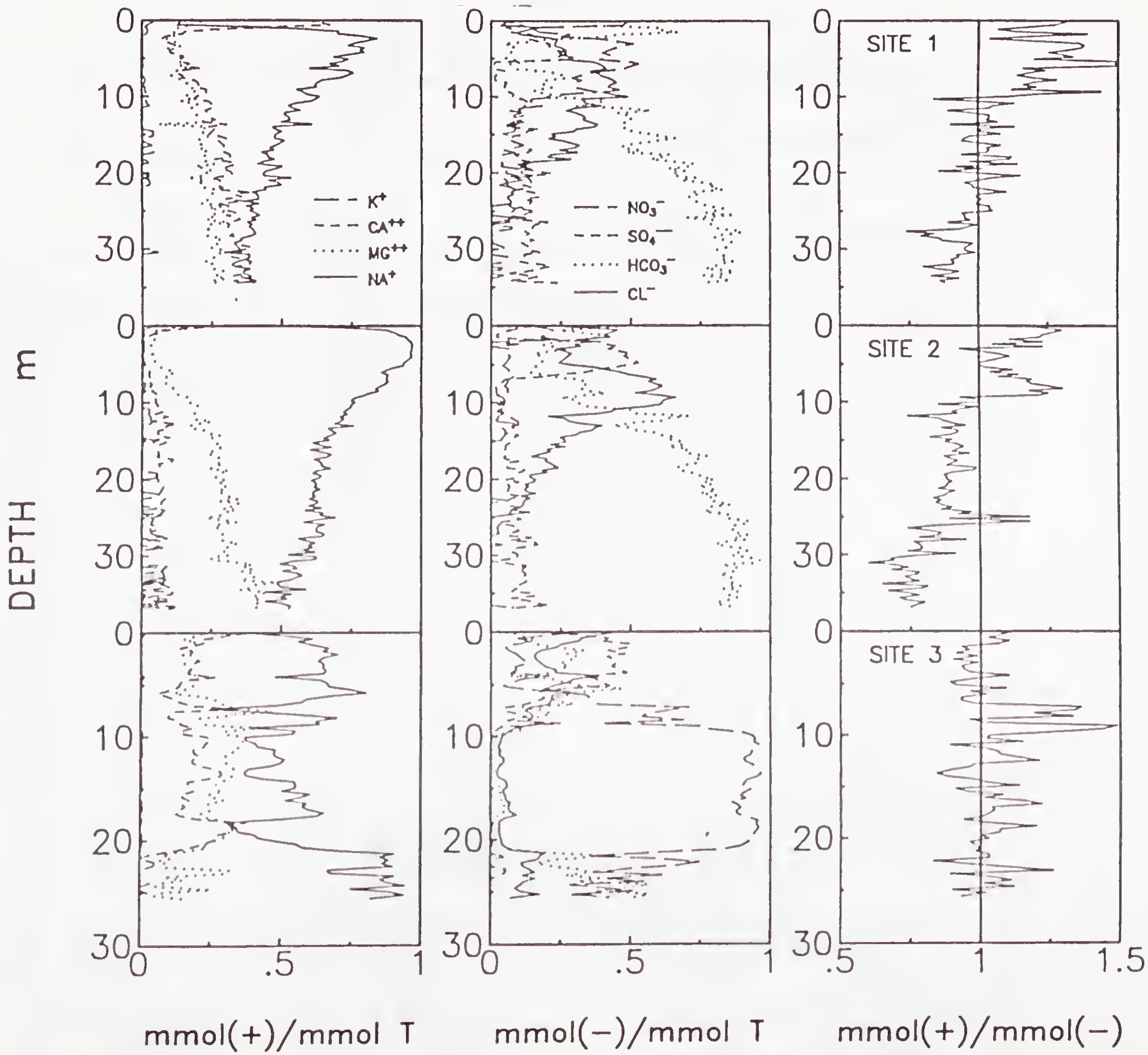

Figure 4. Relative ion distribution and cation:anion ratio for sites 1, 2, and 3.

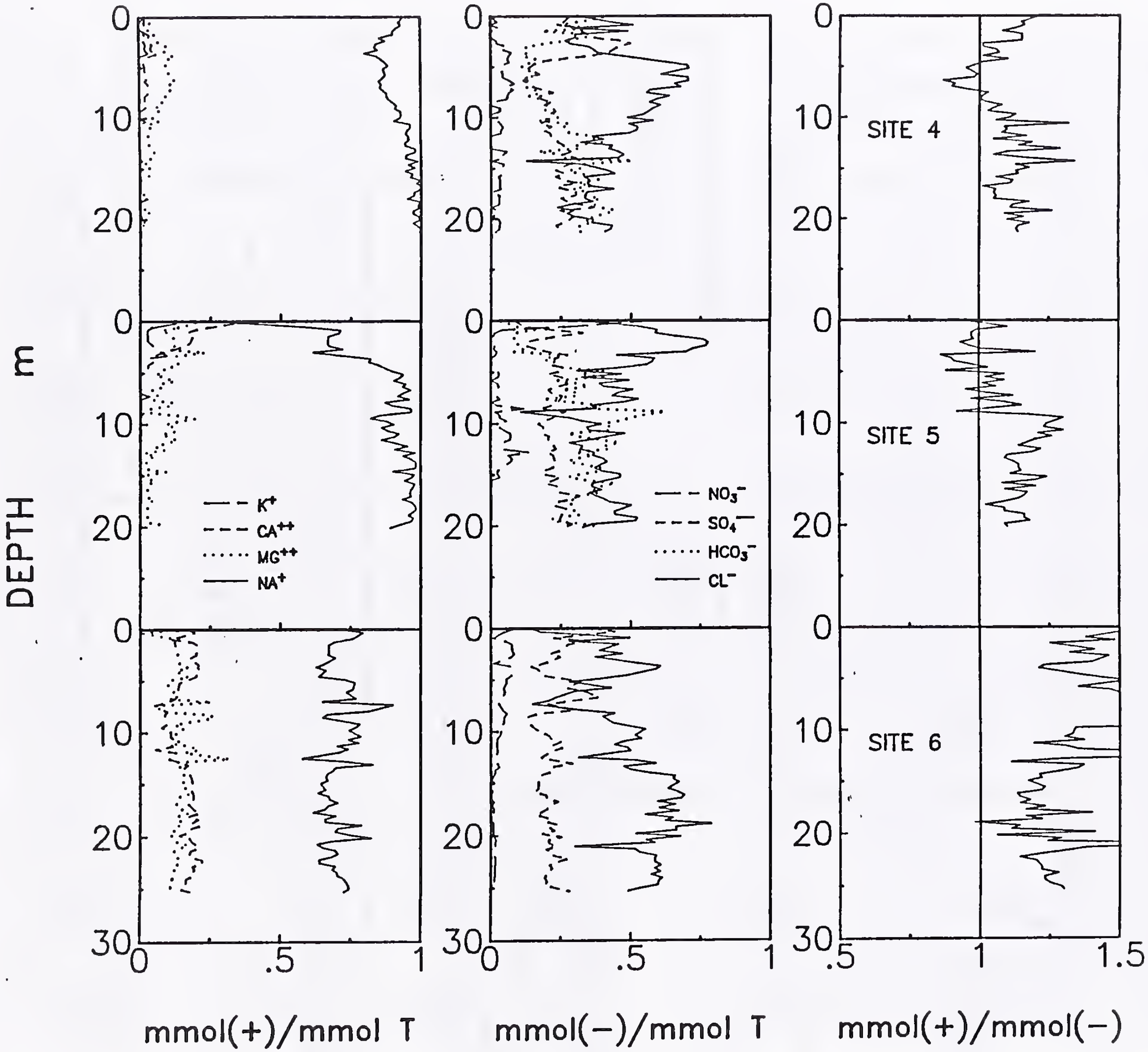

Figure 5. Relative ion distribution and cation:anion ratio for sites 4, 5, and 6.

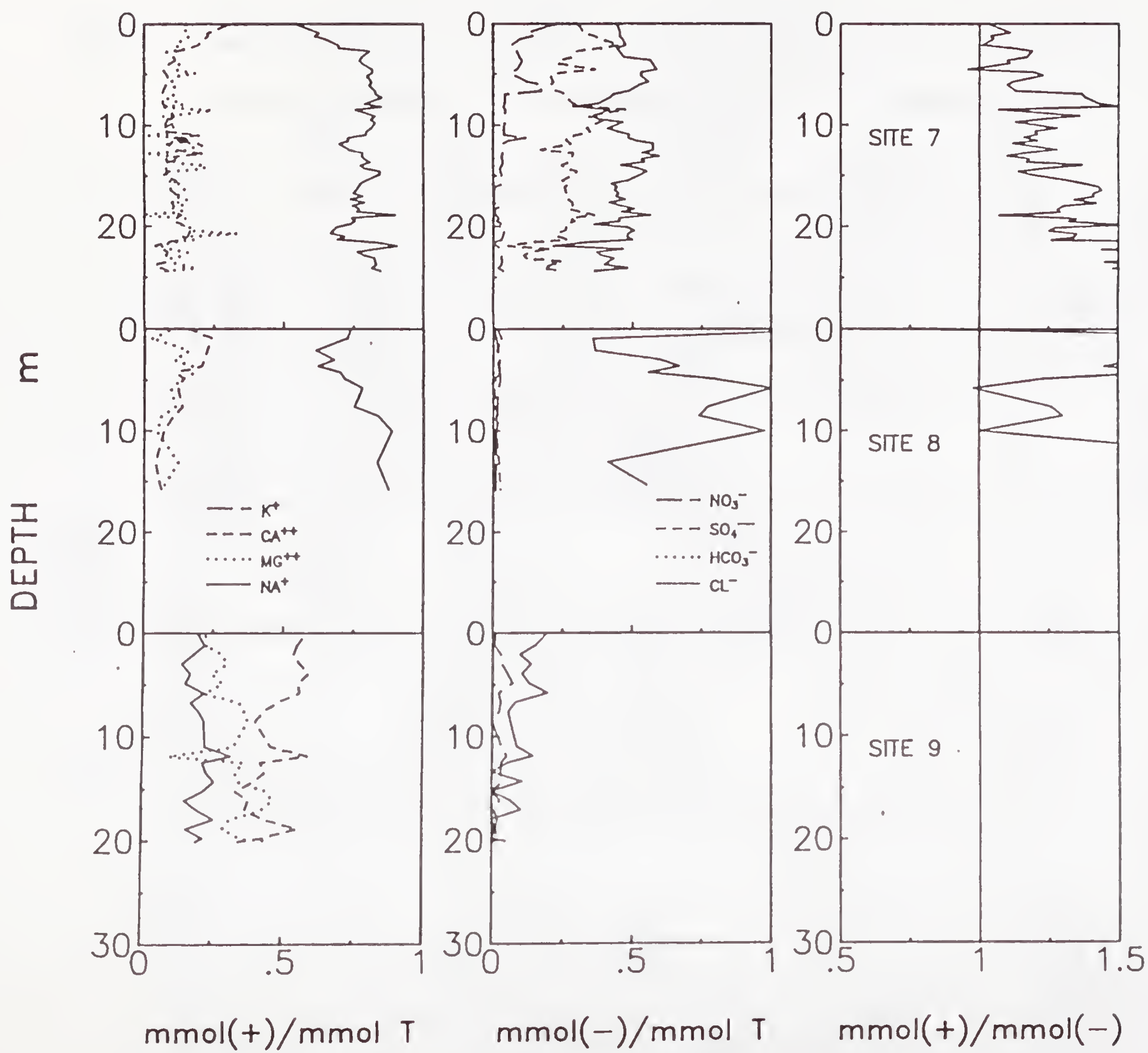

Figure 6. Relative ion distribution and cation:anion ratio for sites 7, 8, and 9.

TITLE: BASELINE STUDY OF SHALLOW GROUNDWATER CONTAMINATION BY PESTICIDES BELOW IRRIGATED FIELDS

SPC: 1.3.02.1.a
1.1.02.1.c

CRIS WORK UNIT: 5422-20790-005

INTRODUCTION

Transport to groundwater of agricultural pesticides applied at the soil surface may require years or even decades, depending upon pesticide properties, soil characteristics, leaching rate, and depth to groundwater. Pesticides are most likely to be found in shallow groundwater underlying areas which have a long history of chemical application. It is important to monitor such shallow groundwater in order to detect early arrival of pollutants, and to yield information useful in predicting the fate of pesticides in other areas.

The purpose of this study is to determine if measurable levels of pesticides have arrived at shallow groundwater in several irrigated areas for which good records of pesticide applications are available. The data will be used to evaluate the influence of pesticide characteristics and agricultural management practices on groundwater pollution potential.

This study was initiated in the fall of 1986; analytical methods development is still in progress, and no results have yet been obtained.

MATERIALS AND METHODS

Sampling Location

Samples of shallow groundwater were obtained from open drains located on the Colorado River Indian Reservation in western Arizona (Fig. 1). The reservation lies along the Colorado River south of Parker, Arizona. Groundwater levels vary from just below the surface near the river, to more than 10m at some locations on the eastern edge of the reservation. Most of the reservation is cultivated, with primary crops being cotton, alfalfa, wheat, and vegetables such as lettuce and cabbage.

Samples of drainage water were taken on 18 November 1986 from eight locations along two drains which run the length of the reservation (Fig. 1). Four liters of water were collected as a grab sample at each location, using a plastic bucket. Each sample was transferred to a glass bottle which was then placed in an insulated storage box for transport back to the laboratory. Samples were refrigerated prior to extraction and analysis.

Analytical Methodology

Assay of pesticides in the groundwater was performed by using a Finnigan 5100SP gas-chromatograph/mass spectrometer (GS/MS) in order to have qualitative and quantitative analysis of unknown compounds simultaneously.

The pesticides in the groundwater samples were extracted and derivatized using EPA methods with slight modification (1,2). The groundwater samples were used within four days to avoid decomposition of organo-chloride compounds. Relatively less-polar organic compounds in the water were fractionated by using the following methods: transfer 1000 ml of water to a 2000 ml separatory funnel and add 20 g anhydrous sodium sulfate and 100 ml methylene chloride followed by vigorous shaking for 2 min. This process was repeated two more times. Extraction of free organic-acid compounds in the water phase was performed as follows: reduce pH below 3.0 and add 100 ml methylene chloride to the water phase. The methylene chloride fractionation was repeated two more times. The resulting methylene chloride fractions were dehydrated by passing through an anhydrous sodium sulfate column and concentrated near to dryness using a Kuderna-Danish flask attached to a rotary evaporator, at as low temperature as possible. Two ml of hexane was used to transfer the residue to another container, and anhydrous sodium sulfate was added. The hexane solution was transferred to a sample vial and concentrated to ca. 0.5 ml. The organic-acid fraction was derivatized by addition of boron trifluoride in methanol.

One microliter samples were injected into the GC/MS. Wide MID scans were used for standard compounds and samples for possible identification of unknowns.

RESULTS

Extractions and analyses are in progress, and no results have yet been generated. If pesticide residues are detected in the initial samples, more extensive sampling at the Colorado River Indian Reservation and at other locations, where shallow groundwater underlies agricultural fields, will be undertaken.

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PERSONNEL

H. Y. Cho and R. S. Bowman

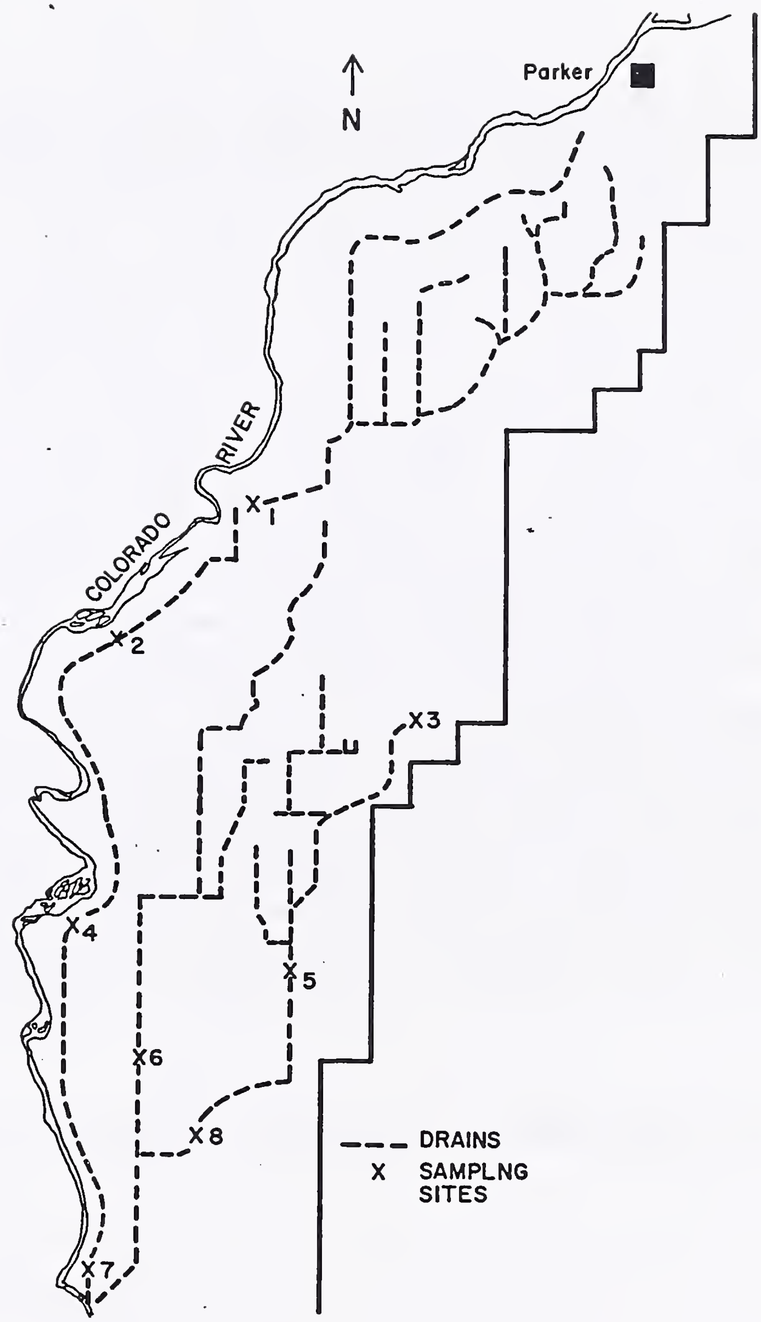

Figure 1. Portion of the Colorado River Indian Reservation, showing the open drain system and the sampling locations.

TITLE: EFFECT OF SOIL WATER HYSTERESIS ON SIMULATED INFILTRATION AND REDISTRIBUTION OF WATER IN A SOIL COLUMN

SPC: 1.3.02.1.a
1.1.02.1.c

CRIS WORK UNIT: 5422-20790-005

INTRODUCTION

A finite difference model for water movement was developed and used to investigate the sensitivity of the computed water content, Θ, and soil water potential, h, to hysteresis in the Θ-h relationship. The model incorporated a simple linear hysteresis algorithm described in an earlier paper (Jaynes, 1984). The hysteretic soil-water characteristic was measured in an earlier study and fit with van Genuchten's equation. The resulting equation parameters were also used to describe the unsaturated hydraulic conductivity, K, as a function of Θ. Simulations were run and compared to the measured results of five cyclic infiltration-redistribution experiments run on a 140-cm long column filled with medium sand. Initial results from the model showed h and Θ to respond more quickly than observed to changes in the boundary conditions. The value used for the saturated hydraulic conductivity was apparently too large in these simulations. Reducing the value by 40% gave excellent agreement between observed and computed h and Θ behavior (Figs. 1 and 2). Additional simulations were run with the hysteretic nature of the Θ-h relationship ignored and either the main wetting or main drying curve used instead. These simulations compared poorly with the observed pressure versus time but provided upper and lower bounds for the hysteretic simulation (Fig. 1). Water contents were simulated equally well for both hysteretic and non-hysteretic conditions (Fig. 2). The discrepancy between Θ results and h results in the three simulations was due to the hydraulic conductivity being a function of Θ. Mass conservation and a steep K-Θ relationship forced all simulations to the same Θ versus time results regardless of hysteresis behavior. Identical h versus time results would be found if K was expressed as a function of h and not Θ. When modeling soil water movement, hysteresis in the Θ-h relationship can be ignored if the parameter of interest, either h or Θ, is considered to control K.

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D. B. Jaynes and R. K. Shen

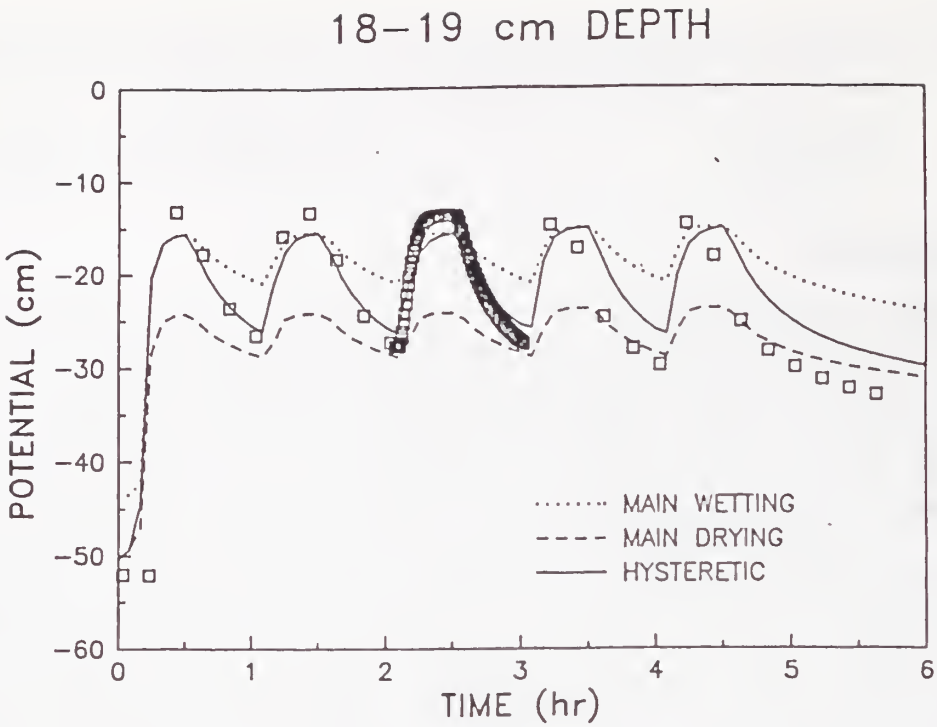

Figure 1. Soil water potential at the 18-19 cm depth versus time during five wetting-drying cycles. Squares represent measured values. Curves are calculated using either a hysteretic θ-h relation or just the main wetting or main drying curve.

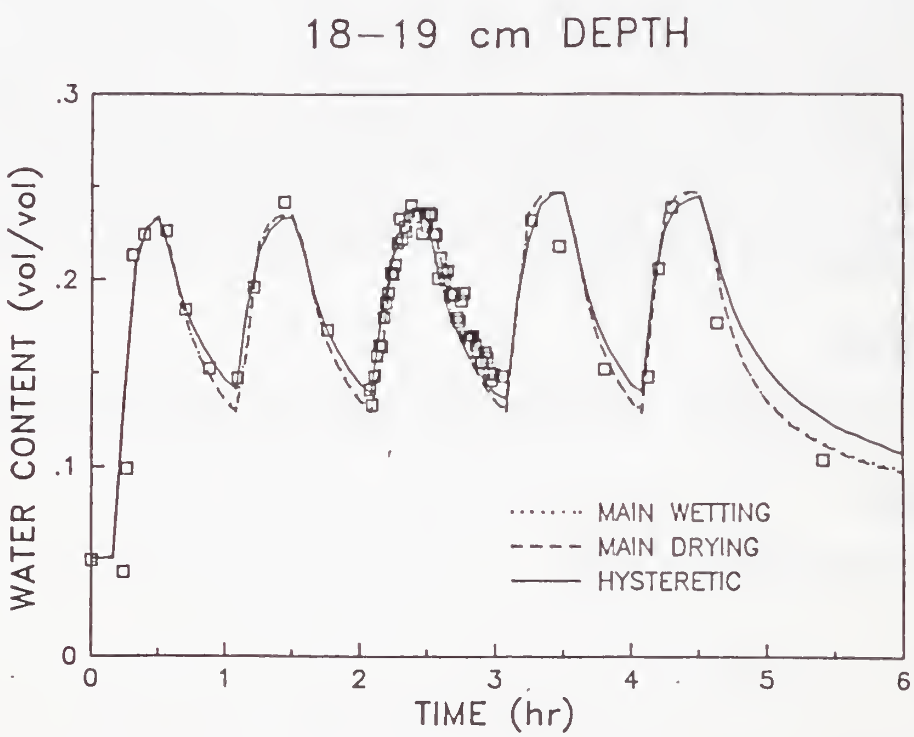

Figure 2. Water content at the 18-19 cm depth versus time during five wetting-drying cycles. Squares are measured values. Curves are calculated using either a hysteretic θ-h relation or just the main wetting or main drying curve.

TITLE: EFFECT OF WATER DEPTH ON INFILTRATION

SPC: 1.3.02.1.a
1.1.02.1.c

CRIS WORK UNIT: 5422-20790-005

INTRODUCTION

Ground water recharge using water containing suspended solids will result in a clogged surface layer and subsequently lower the infiltration rate. As the layer is formed causing a significant decrease in the infiltration rate, negative pressures will develop below the clogged layer. Reduction in the hydraulic conductivity of the clogged layer will depend, in part, upon the seepage forces acting across the layer. Factors affecting the seepage forces include the infiltration rate, water depth, and head loss across the layer.

PROCEDURE

A laboratory experiment was conducted using 2 columns packed with a loamy sand material. Each column consisted of a 2.75 m length of 10-cm I.D. polyvinyl chloride pipe filled with 6 cm of pea gravel at the bottom and 240 cm of soil above that. Initially, both columns were saturated from the bottom. Tensiometers were located at 5, 25, 65, 145, and 225 cm from the soil surface. A constant head of 20 cm of water was maintained above the soil surface by means of a Mariotte siphon. After several days of infiltration, when the infiltration rate was relatively constant, a clogged layer was developed by adding a solution containing Avondale loam. The equivalent of 1-cm depth at a density of 1.5gm/cm^3 was added. After 8 days, the water depth in one column was raised to 85 cm while the other remained at 20 cm. The higher head was then lowered back to 20-cm depth after another 14 days. The above procedure was repeated using a 5-cm layer of organic muck instead of the loam as the clogging material. The head was not lowered to the original depth at the end of the test.

RESULTS

The change of infiltration with time is shown in Figure 1 for the Avondale loam layer. Addition of the clogged layer reduced the infiltration rate (I), from 56 to about 30cm/day in one column and from 50 to 36cm/day in the other. Raising the water depth to 85 cm increased I from 30cm/day to about 40cm/day during the first day and then gradually increased to 46cm/day after 14 days. When the water depth was lowered to 20 cm, I decreased to about 30cm/day. The hydraulic impedance, r_s, which is the thickness of the sealing layer divided by its hydraulic conductivity, is shown in Figure 2. The impedance increased from 0.02 days to a little over 2 days after the addition of the clogged layer. When the water depth was increased, r_s increased to 3.6- 3.9 days. The increase in r_s indicates that the increased water depth resulted in compaction of the clogged layer. Lowering the water depth did not change r_s; thus, compaction of the clogged layer is an irreversible process. In the column that remained at constant head, I

decreased from 40 to 36cm/day. The impedance gradually increased from 1.3 to 2.7 days after the clogged layer was added.

The initial infiltration rate of the column receiving the organic muck clogging material was about 60cm/day (see Fig. 3). After the muck was added to the column, the rate decreased to 35-40cm/day. Over the next 14 days, I increased to 53cm/day and 70cm/day for the 2 columns. When the water depth was increased in the one column, the infiltration rate immediately increased to 110cm/day and then decreased to 73cm/day after one day. The increase in I then continued for the next 10 days. On the column that remained at constant depth, I continued to increase until the end of the experiment.

Increasing the head to 90 cm should have increased the infiltration 2.2 times if the hydraulic properties did not change. Immediately after the increase in water depth, the infiltration was 110cm/day which was an increase of 2.1. The infiltration then decreased to 73 cm after one day indicating compaction due to the higher head. The change in r_s with time is shown in Figure 4. Accurate impedance values were not obtained the first day because of slow response time on the tensiometers as the pressure was changing. A slight increase was noted on the second day after the head was increased. The continued increase in infiltration indicates that the organic clogged layer is becoming more permeable due to decomposition or possible channelling within the layer because of microbial gas production. The degradation of the clogged layer was observed on both high and low head columns.

SUMMARY AND CONCLUSIONS

A laboratory column experiment was conducted to study the effect of water depth on hydraulic impedance of clogging layers. Two clogging materials were used, one with a high organic matter content, taken from a mucky pond bottom, and one with essentially no organic matter, taken from a field soil (loam).

The low-organic matter clogging layer showed a drastic increase in hydraulic impedance with increasing water depth. The impedance of the clogged layer with the high organic matter content, however, was relatively unaffected by water depth. Apparently, biological activity in the high-organic-matter layer caused continued rearrangement of particles and breakups of layers in this material. This prevented significant increases in hydraulic impedance.

These results showed that deep infiltration basins can indeed produce more impeding clogging layers than shallow basins, especially if the clogging material is primarily inorganic. Shallow basins, thus, could give similar and even higher infiltration rates than deep basins. Shallow basins also have a higher turnover rate of the water, which discourages development of suspended algae and reduces the possibility of bottom clogging due to algal deposits.

PERSONNEL

H. Bouwer, R. C. Rice, and J. B. Miller

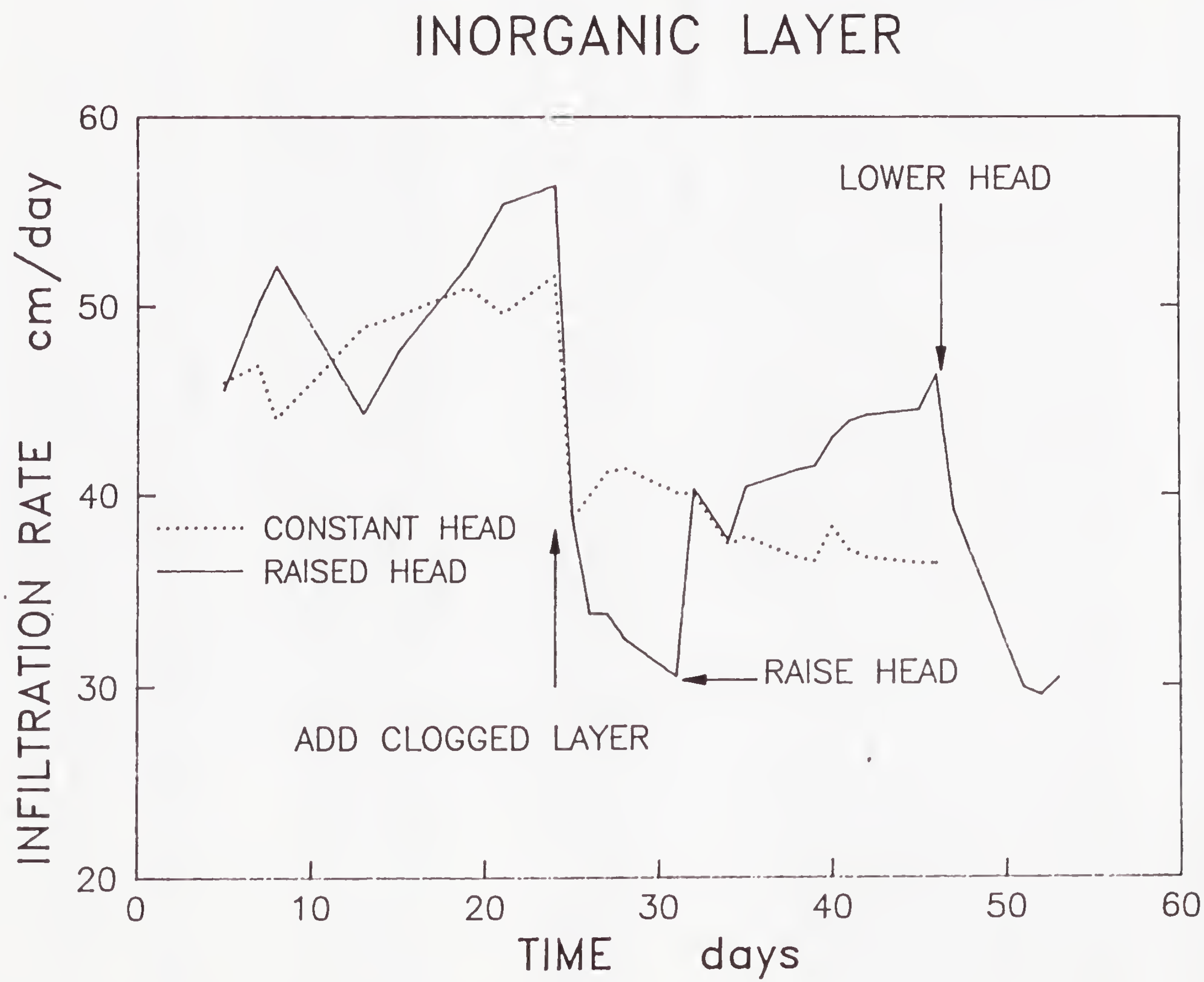

Figure 1. Infiltration with time for inorganic clogged layer.

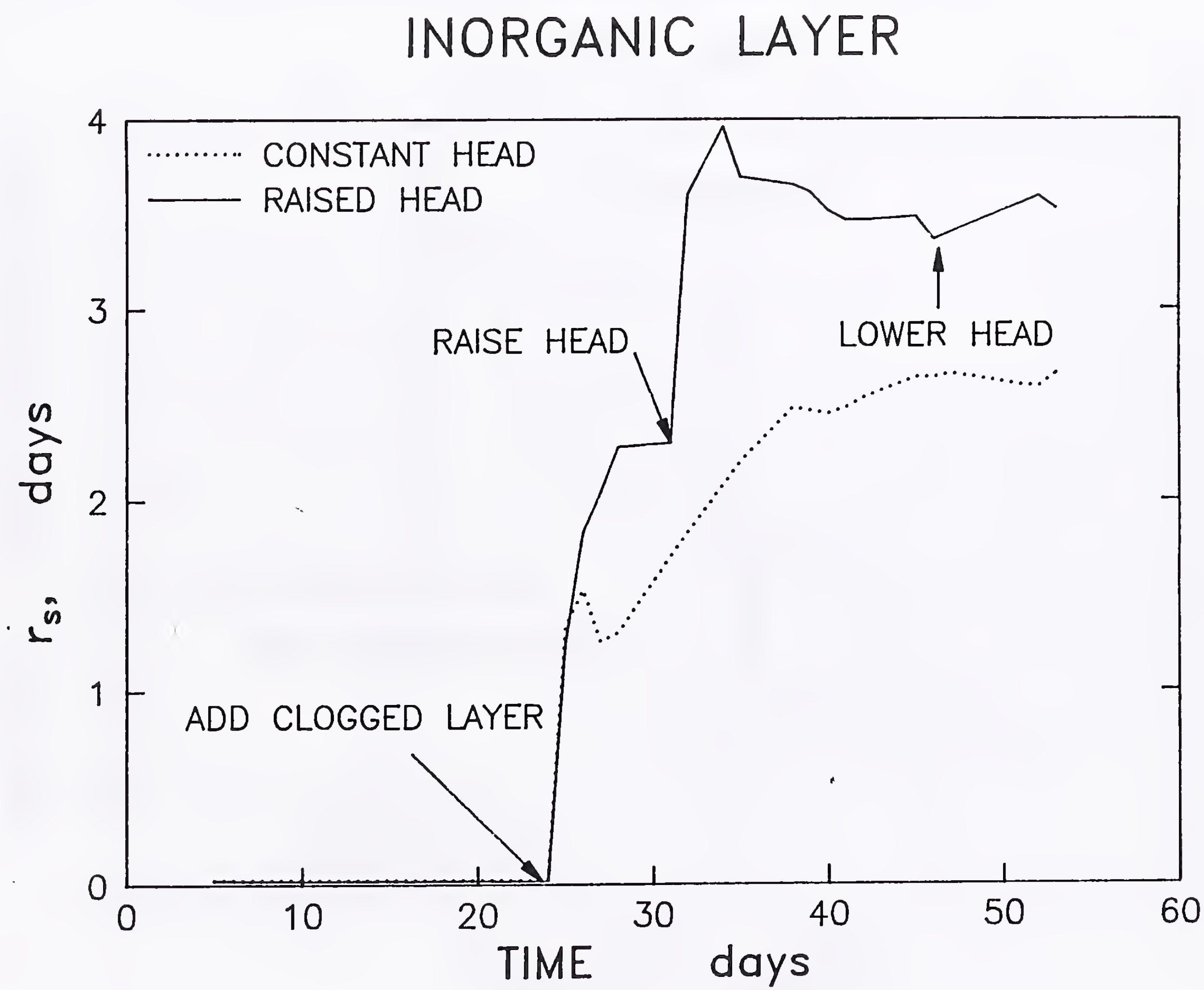

Figure 2. Impedance, r_s, with time for inorganic clogged layer.

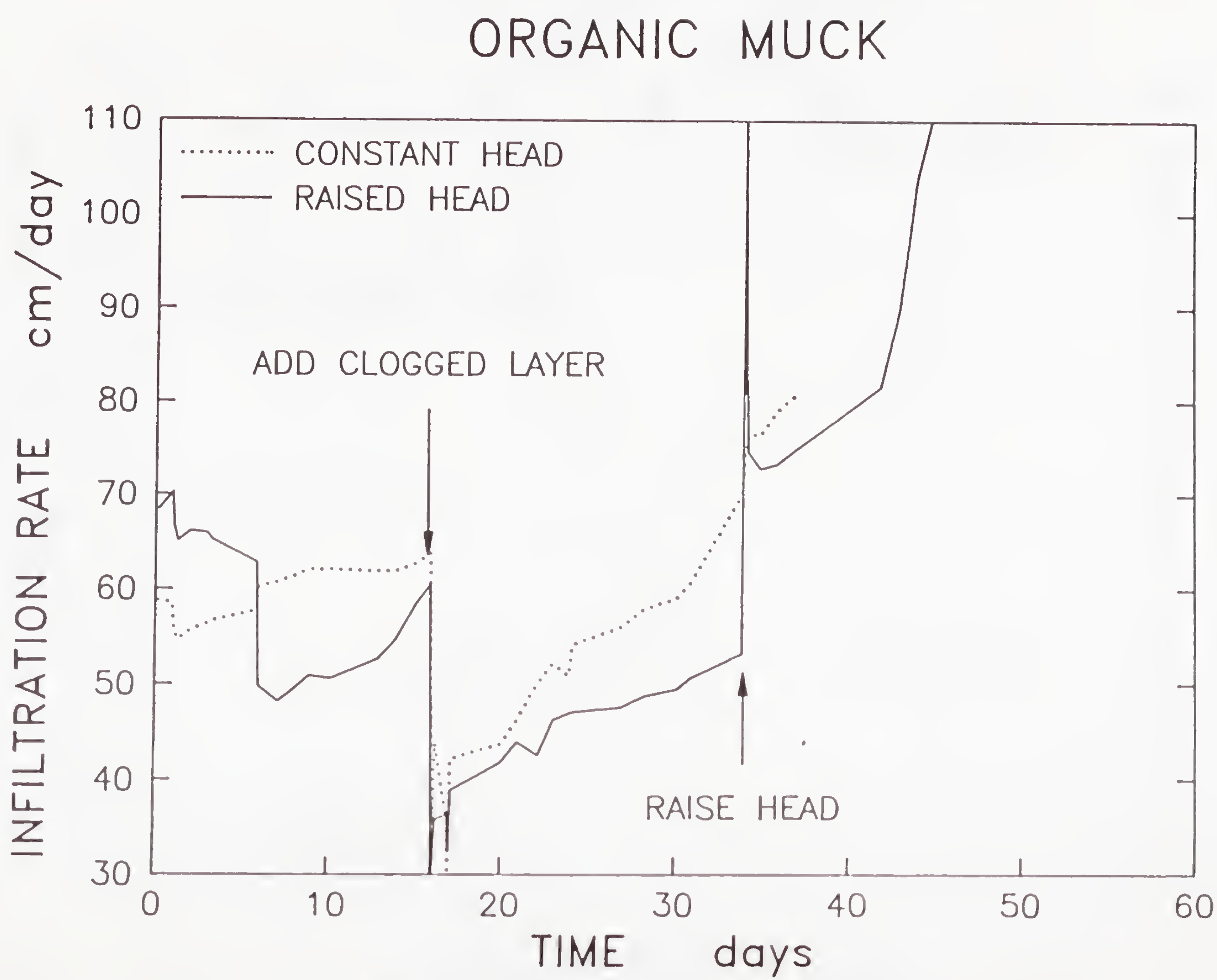

Figure 3. Infiltration with time for organic muck clogged layer.

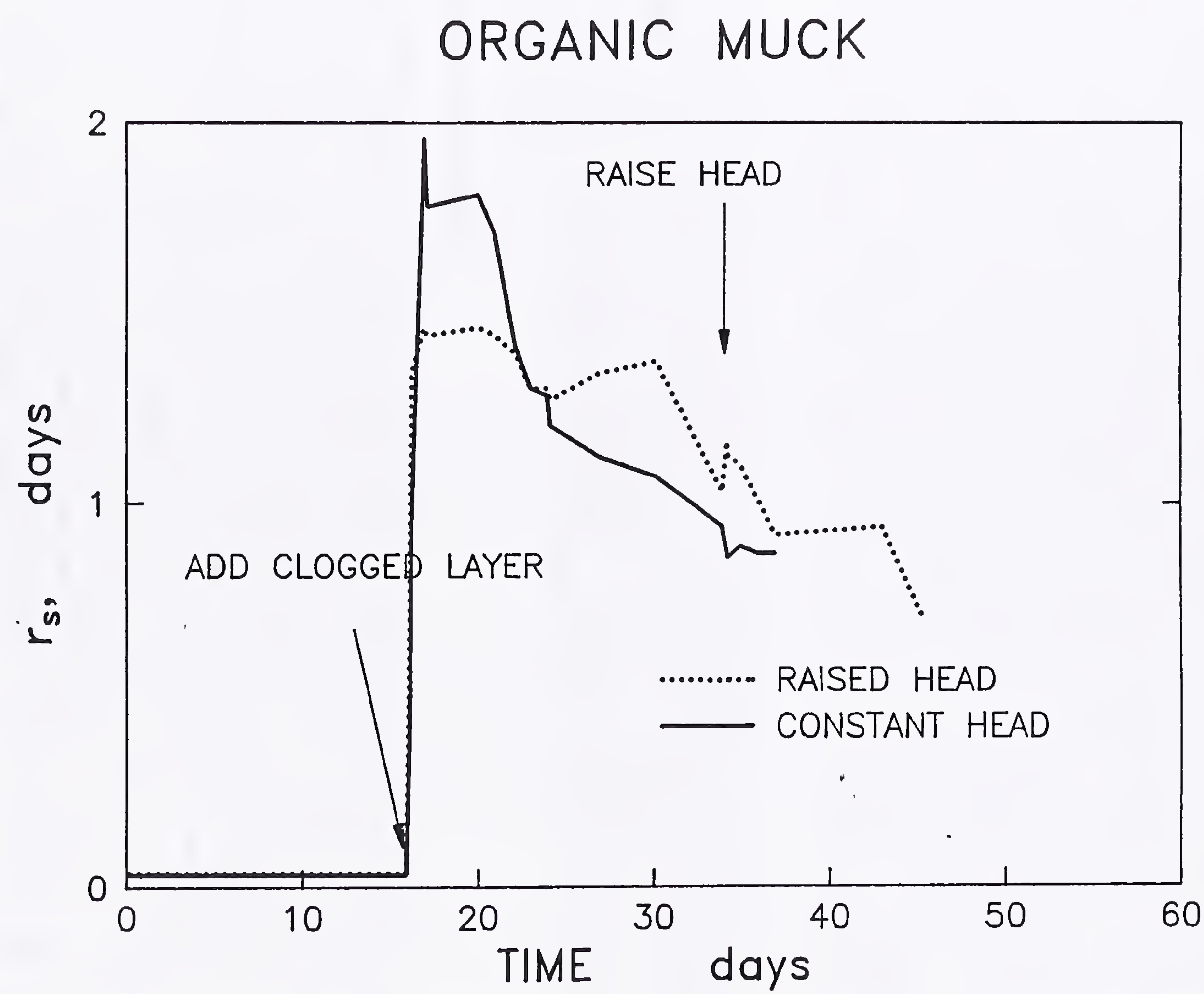

Figure 4. Impedance, r_s, with time for organic muck clogged layer.

TITLE: HYSTERETIC BEHAVIOR OF A MEDIUM SAND

SPC: 1.3.02.1.a
1.1.02.1.c

CRIS WORK UNIT: 5422-20790-005

INTRODUCTION

In the past ten years, considerable interest has been shown in developing mathematical algorithms for describing the hysteretic behavior of the soil water content - soil water pressure, Θ-h, relationship (Dane and Wierenga, 1975; Gillham et al., 1976; Hoa et al., 1977; Kool and Parker, in press). Unfortunately, little critical evaluation of these various algorithms has been conducted. Jaynes (1984) compared four algorithms by their ability to predict scanning curves, degree of non-conservative pumping, and performance as part of a soil water advection model. Although sufficient data exist to reliably evaluate the different models against the first and last criteria, pumping behavior has not been sufficiently studied to quantitatively compare the models with actual soil behavior. Instead Jaynes (1984), following Klute and Heerman (1974), assumed cyclic scanning curves would close on themselves and thus exhibit a conservative behavior. While predicted by various pore models (Mualem, 1974, 1984) this behavior has not been clearly documented for soil.

This study is divided into two parts. In the first, we wished to measure the hysteretic behavior of a soil and to document its behavior during cyclic pressure variations. In the second part of the study we used the hysteresis data to calibrate a soil water advection model and then validated the model using measured data from a series of infiltration-redistribution experiments. Results of the first phase of the study are reported here with the second phase reported in an accompanying paper.

MATERIALS AND METHODS

Measurements were made on a clean medium sand that had been sieved to retain only the 0.25- to 0.5-mm fraction. The sand was carefully packed into a lucite column, 140-cm long by 10-cm diameter. Water content measurements were made by gamma attenuation. A Cs^{137} source of approximately 3 GBq (80mCi) was used in conjunction with a 1.27-cm NaI(Tl) scintillation crystal mounted on a DuMont K1780 photomultiplier tube. Details of the gamma ray counting equipment are given in Reginato and Stout (1970). The source and detector were mounted on a movable platform that maintained their separation and orientation. The platform was driven by an electric motor with the column placed between the source and detector. Figure 1 illustrates the experimental apparatus. The gamma rays were collimated between two narrow slits. The slit at the source was 19 mm wide and 4 mm high while that at the detector was 19 mm wide by 5 mm high. Only gamma rays within .025 MEV of the .66 MEV peak for Cs^{137} were counted.

Soil water potentials were measured with 22 tensiometers located at various distances down the column. The tensiometers were connected to a

pressure transducer (Setra, Model 237) through a 24 position scanivalve (Scanivalve Corp., Models W0602/1P-24T wafer and WS5-24 solenoid drive). Two additional tensiometers were connected to known potentials and served as calibration points during the experiments. The accuracy of the pressure head measurements was within ±0.15cm.

After packing the column we consolidated the sand by slowly saturating the sand from below and then allowing it to rapidly drain. All water used consisted of a 0.005 M solution of $CaSO_4$ to which .0015 moles/L of sodium azide was added to control microbial growth. The sand settled approximately 5 mm during the process while no further settling was observed during the remainder of the experiment. After drainage, an air stream was forced through the column to dry the sand. The bulk density of the sand at the location of each tensiometer was then measured. Next the column was flushed with CO_2 gas and slowly saturated from below. After saturation, the saturated water content at each tensiometer position was measured.

Hysteresis curves were measured for the location 19 cm from the top by controlling the position of the water table at the bottom of the column. Initially, we tried to change the water table position slowly with a peristaltic pump while continuously taking soil water potential and water content measurements at the 19-cm depth. However, the unsaturated hydraulic conductivity of this uniformly sized sand decreased rapidly as the sand dried and equilibrium could not be maintained in this way. Instead, the water table was repositioned in approximately 4-cm increments and measurements were made only after the water content had stabilized (4-24 hr). This proved to be a very slow process but was necessitated by the low conductivities of the unsaturated sand. The main drying and wetting curves were measured four times in this manner. Van Genuchten's (1980) equation for describing soil retention data was fit to the two main branches by a non-linear regression procedure.

After measuring the main drying and wetting curves, primary rewetting and secondary redrying curves were measured from three points on the main drying curve. Three primary redrying curves and secondary rewetting curves were also measured from the main wetting curve. A last set of measurements to test for pumping effects consisted of cycling nine times between two pressures starting from a point on the main drying curve.

Calibration

The equation describing gamma ray attenuation through the column is

$$I = I_o \exp\left\{-\rho_s \mu_s X_s - \rho_w \mu_w X_w - \rho_c \mu_c X_c\right\} \qquad (1)$$

where I = count rate of attenuated beam
I_o = count rate of unattenuated beam
ρ_s = bulk density of sand
μ_s = attenuation coefficient for sand
X_s = beam path length through sand

ρ_w = density of water
μ_w = attenuation coefficient for water
χ_w = beam path length through water
ρ_c = density of column walls
μ_c = attenuation coefficient of column walls
χ_c = thickness of side walls.

Since ρ_c, μ_c and χ_c are constant we can measure the attenuation through the empty column, I_o', and substitute into Eq. 1. Also, since $\rho_w = 1.0$ and $\chi_w = \Theta\chi_s$ where Θ is the volumetric water content, Eq. 1 becomes

$$I = I_o' \exp\{-\chi_s(\rho_s\mu_s + \Theta\mu_w)\} \tag{2}$$

which can be solved for Θ if the other parameters are known.

To measure μ_s, oven-dry sand was packed at a known bulk density into 5 plastic cylinders. The cylinders were 3.2-cm in diameter and 3.0-, 5.0-, 7.0-, 9.0-, and 11.0-cm long. Attenuated count rates were measured for each cylinder lengthwise. Rearranging Eq. 2 with $\Theta = 0$ gives:

$$\ln I - \ln I_o' = -\mu_s(\chi_s\rho_s) \tag{3}$$

which can be solved for μ_s by linear regression. Table 1 and Fig. 2 show the data and results of the calibration. A similar method was used to calculate $\mu_w = .0864$.

The errors involved in using Eq. 2 to calculate Θ depends on the counting rate for the gamma rays. The emission of gamma rays being a random event the standard deviation is the square root of the count rate. As example 100 counts over a given time period has a standard deviation of 10 counts. To obtain a coefficient of variation of 1%, 10^4 counts must be made. Using error propagation analysis, we can estimate the maximum measurement precision attainable from calculations of the probable error. For a function $F(\overline{\chi}) = F(\chi_1, \chi_2, \chi_3 \ldots, \chi_n)$ the probable error $\sigma_{F(\chi)}$ is estimated by

$$\sigma_{F(\overline{\chi})} = \left[\sum_{i=1}^{n}\left(\frac{\partial F(\overline{\chi})}{\partial \chi i}\sigma_{\chi i}\right)^2\right]^{1/2} \tag{4}$$

Rearranging Eq. 2 for Θ, assuming the error in measuring μ_w and μ_s is negligibly small, and letting $\sigma_I = \sqrt{I}$ and $\sigma_{I_o'} = \sqrt{I_o'}$ we have

$$\left[\left(\frac{\partial\Theta_w}{\partial I}\sqrt{I} + \frac{\partial\Theta_w}{\partial I_o}\sqrt{I_o'}\right)^2\right]^{1/2} \tag{5}$$

$$= \frac{1}{\mu_w\chi_s}(1/I + 1/I_o')^{1/2}$$

Obviously the highest counts have the lowest probable error. In our experiment all counts were sufficiently great that $\sigma_\Theta < 0.005$.

RESULTS

Table 2 shows the bulk density, maximum water content and saturation fraction measured for 22 depths down the column. Densities were very uniform with a mean of 1.46 g/cm^3 and a coefficient of variation of 0.0078. The saturation fraction is very high at each position but decreases near the top of the column. Apparently the volume of entrapped air was greater near the top because the column was saturated from below.

Figure 3 shows the measured main drying and wetting curves. The different symbols used in Fig. 3 represent the four separate times the curves were measured. The four sets of measurements for each curve agree very well with each other. The solid curves represent the best nonlinear fit to the data for van Genuchten's (1980) equation with two unknowns. Values for the equation parameters are also listed in Fig. 3. The saturated water content of 0.359 does not represent the total porosity but rather it is a rewet water content that reflects the volume of entrapped air in this column. The volume of entrapped air is very reproducible under the conditions used here.

The series of rewet scanning curves is shown in Figure 4. The three curves departed from the main drying curve at potentials of -21.8, -21.9, and -24.8 cm. The potentials were increased by about 18 cm for each curve and then lowered again to close to the original transition pressure (Table 3). In each case, the secondary drying curves returned to slightly but significantly lower water contents than where the cycles started.

Figure 5 shows the primary drying curves corresponding to transition pressures of approximately -13, -14, and -17 cm (Table 4). Cycles 2 and 3 in Fig. 5 represent 3 and 2 dry-rewet cycles respectively. Although the shape of each cycle is different the scanning curves do return to the same water content when returned to the original transition pressure.

Pumping Effect

The lack of closure for the wetting primary scanning curves in Fig. 4 suggest that the domain theories of Mualem (1974, 1984) may be inadequate and that we shouldn't expect conservative behavior when the pressure is cycled between two pressures. Figure 6 shows the results of the 9 pumping cycles that were initiated from the main drying curve. The transition points for each cycle are also listed in Table 5.

These cycles can be divided into three parts; cycles starting at points 1 and 2 in Figure 6 and ending at point 3; cycles starting at points 4 and 5 ending at point 6; and the last three cycles starting at point 7 and ending at 10. The first two cycles are identical within the precision of measurement. The transition to the next set of cycles takes place from point 3 to 4 where the pressure is increased by only 5 cm rather than by 8 cm as in the first two cycles. The next two cycles

(Fig. 7) between points 4 and 6 also are identical but once again when the pressure is increased by a smaller amount from point 6 the water content decreases further to point 7. The last three cycles also appear to be identical once the transition is made from point 7 to 8 (Fig. 8).

Discussion

The original intent of this phase of our research was to measure the main hysteresis curves for input to a numerical model describing water movement in this soil. The main drying and wetting curves appear to be very reproducible despite the presence of entrapped air, the volume of which is reproducible after each rewetting. The data could be fit very closely using van Genuchten's (1980) five parameter model reduced to two unknowns, α and n. The saturated and residual water contents were estimated from the data as .359 and .05 respectively and m was considered a function of n, m = 1 -1/n. Additional least squares analyses were performed by regressing α, n, and Θ_r as well as α, n, Θ_r, and Θ_s. Little reduction in the total sum-of-squares was provided by these regressions (Table 6) and they also resulted in Θ_r values greater than the minimum Θ observed. For these reasons, results from the two term regressions were used.

The Θ-h relationship for this sand was very steep with hysteresis measurable only over a range of about 35 cm. The rapid and distinct draining of the sand is not surprising given the uniformity of particle and presumably pore sizes. This rapid decrease in Θ with decreasing h also appears to cause the K(Θ) value to decrease rapidly. Water movement at pressures below -40 cm was extremely slow and required weeks for equilibrium to be established.

The scanning curves appeared much less stable and reproducible. During pressure cycling tests the curves appeared to be conservative provided the pressure was cycled between exactly the same two values. Increasing the pressure to a smaller value during rewetting caused the soil to return to a lower water content when the pressure was decreased back to the transition point. This behavior contradicts the domain theories of Mualem (1974, 1984), but appears to mimic the behavior of several empirical hysteresis models (Jaynes, 1984). The cause of this pumping effect is unclear, but since this soil consisted of a rigid matrix free of microbial activity, variability of entrapped air and a more complicated dependence of entrapped air on the wetting-drying history of the soil would appear to be the cause. Further experiments, including more poorly sorted soils, must be performed to verify these findings and better quantify the pumping effect and the conditions under which it is observed.

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PERSONNEL

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Table 1. Cylinder thickness, sand bulk density, gamma ray count rate and $\rho_s \chi_s$ for each cylinder used to calculate μ_s.

thickness (cm)	bulk density (g/cm^3)	count rate (cps)	$\rho_s \chi_s$ (g/cm^2)
3	1.49	358.0	4.47
5	1.51	288.6	7.55
7	1.49	230.2	10.43
9	1.44	187.8	12.96
11	1.49	141.2	16.39

Table 2. Depth from sand surface, bulk density, maximum measured water content Θ_{max}, and degree of saturation S at 22 locations along the Θ column.

Depth (cm)	Bulk Density (g/cm^3)	Θ max vol/vol	S
4	1.46	.363	0.807
13	1.47	.385	0.864
19	1.47	.396	0.888
25	1.45	.418	0.922
31	1.46	.407	0.905
40	1.45	.407	0.898
52	1.47	.407	0.913
61	1.48	.407	0.921
70	1.46	.418	0.930
73	1.48	.396	0.896
76	1.47	.428	0.962
79	1.46	.428	0.954
82	1.45	.428	0.946
88	1.46	.428	0.954
91	1.45	.440	0.970
94	1.49	.407	0.929
97	1.46	.431	0.959
100	1.47	.428	0.960
103	1.48	.428	0.969
106	1.45	.439	0.969
112	1.47	.428	0.960
130	1.47	.417	0.940

Table 3. Water content (vol/vol) and pressure, h(cm), at transition points for scanning curves from main drying curve.

Curve No.	Transition Point at low Pressure head		Transition Point at high pressure head	
	Θ	h	Θ	h
1-4	.198	-24.8	.293	-13.6
	.193	-24.5		
2-5	.278	-21.9	.310	-13.9
	.266	-21.9		
3-6	.299	-21.8	.335	-12.6
	.295	-21.3		

Table 4. Water content, Θ (vol/vol), and pressure, h (cm), at transition points for scanning curves from main wetting curve.

Curve No.	Transition Point at low Pressure head		Transition Point at high pressure head	
	Θ	h	Θ	h
1	.184	-17.2	.150	-22.8
	.188	-17.2		
2	.280	-13.7	.204	-21.1
	.281	-13.8	.219	-21.4
	.275	-14.0	.221	-21.3
	.281	-14.0		
3	.308	-12.6	.262	-19.5
	.304	-13.1		
	.309	-12.6	.262	-19.4

Table 5. Water contents, Θ (vol/vol), and pressures, h (cm), at transition points during pumping test.

Transition Point	Transition Point of low Pressure head		Transition Point of high Pressure head	
	Θ	h	Θ	h
1	.277	-21.9		
			.310	-13.9
2	.266	-21.9		
			.321	-13.0
3	.272	-21.8		
			.286	-16.9
4	.255	-21.9		
			.312	-13.2
5	.259	-21.8		
			.319	-12.8
6	.256	-21.8		
			.279	-17.5
7	.250	-22.0		
			.276	-16.0
8	.245	-21.7		
			.274	-16.9
9	.241	-21.8		
			.273	-16.9
10	.242	-21.9		

Table 6. Regression parameters for main drying and wetting curves and the sum-of-squares, SS, for each step of the regression analysis.

Type of Curve	Fitting Method		n	α	θ_r	θ_s	SS
Main Drying Curve	Linear Regression		4.774	.0421	.0500	.359	.022
	Non-linear	Two Parameters n, α	8.812	.0402	.0500	.359	.0023
		Three Parameters n, α, θ_r	10.174	.0411	.0714	.359	.0015
		Four Parameters $n, \alpha, \theta_r, \theta_s$	10.259	.0410	.0780	.358	.0015
Main Wetting Curve	Linear Regression		4.322	.0651	.0500	.359	.0048
	Non-linear	Two Parameters n, α	5.219	.0630	.0500	.359	.0019
		Three Parameters n, α, θ_r	5.717	.0638	.0610	.359	.0012
		Four Parameters $n, \alpha, \theta_r, \theta_s$	5.762	.0636	.0613	.357	.0012

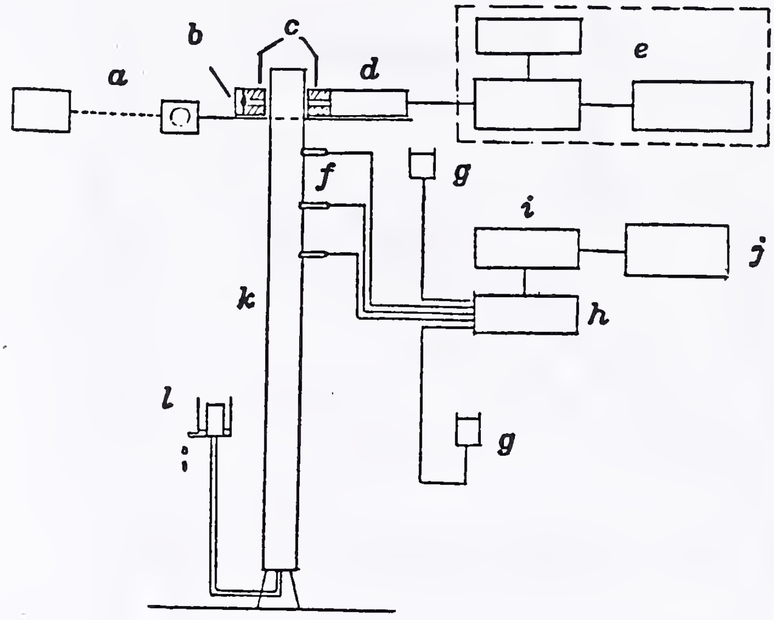

Figure 1. Schematic of equipment used in experiment: a, electric motor - gear drive; b, γ-ray source; c, colimators; d, γ-ray detector; e, amplifier - counter system; f, tensiometers; g, reference potentials; h, scanivalve; i, pressure transducer; j, recorder; k, column; l, controlled head outlet

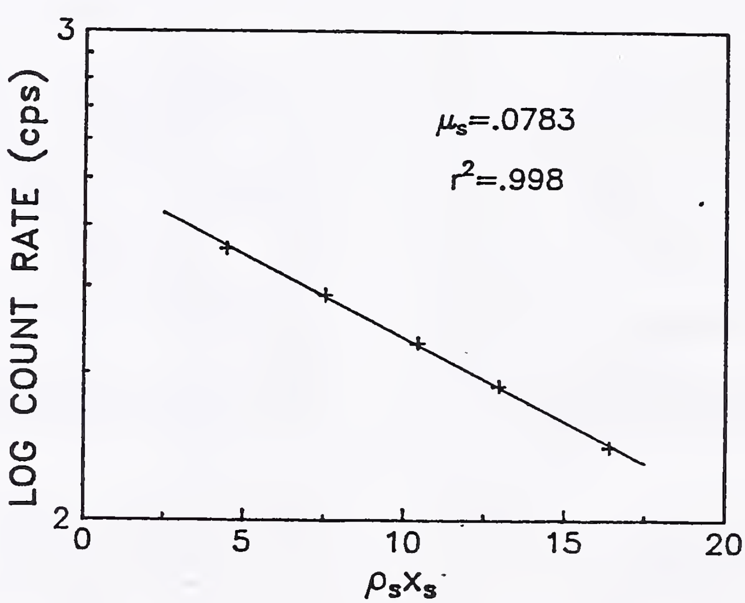

Figure 2. Calibration curve for μ_s

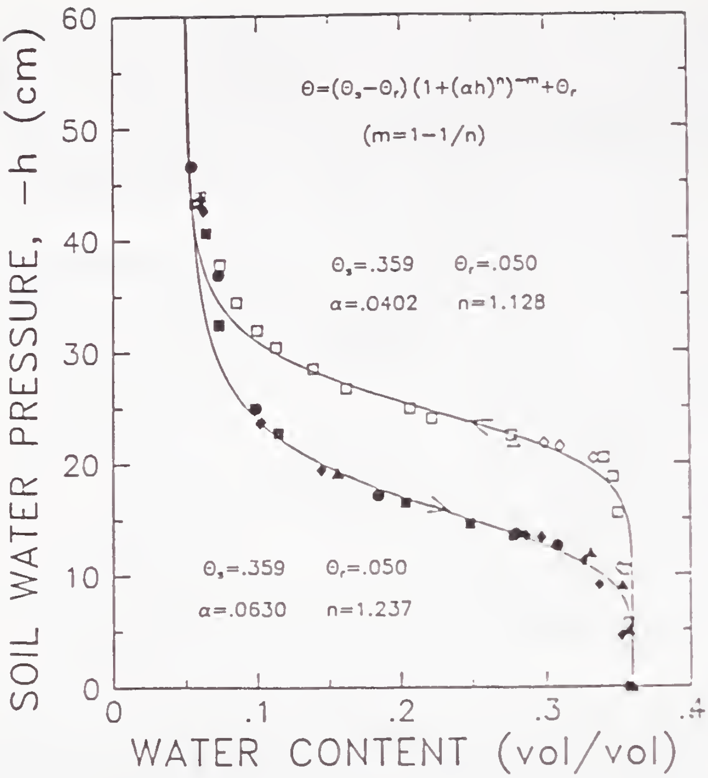

Figure 3. Main drying and wetting curves. Different symbols represent the four times each curve was measured.

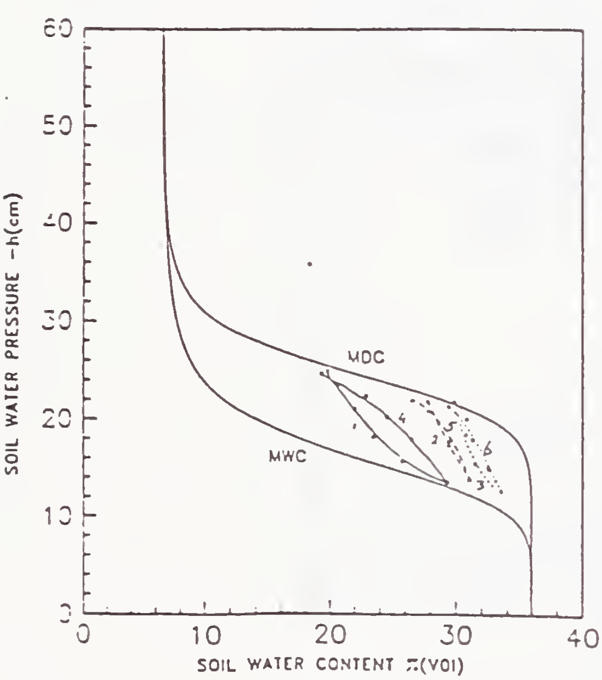

Figure 4. Scanning loops starting from three places on the main drying curve

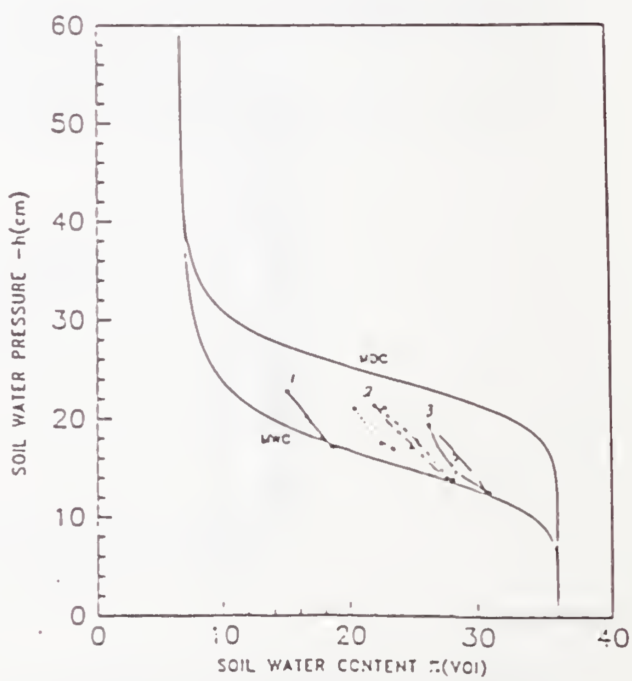

Figure 5. Scanning loops starting from the main wetting curve

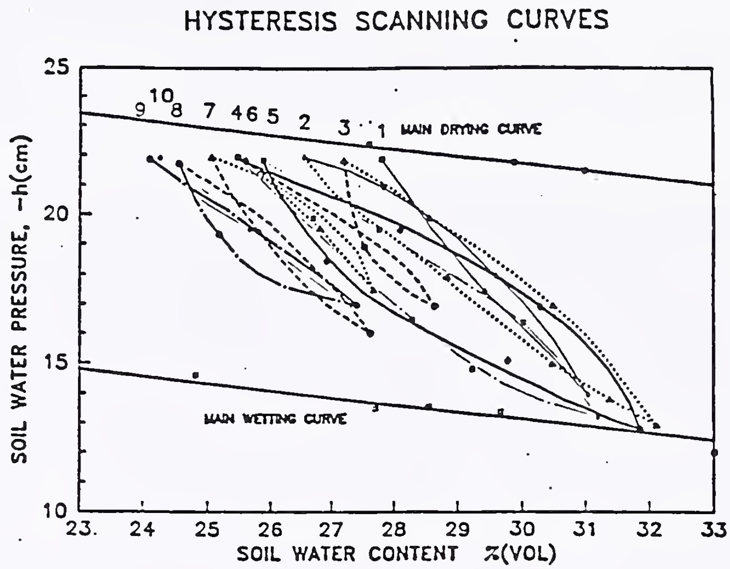

Figure 6. Nine pumping cycles starting from the main drying curve. Numbers identify order of each cycle.

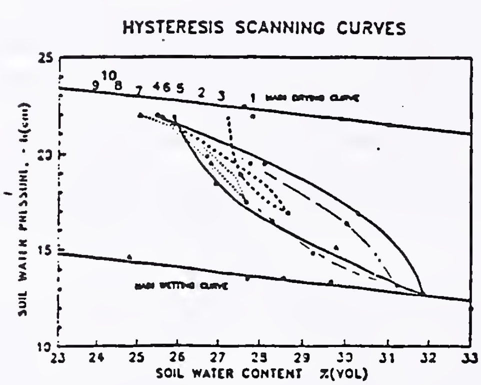

Figure 7. The third, fourth, fifth, and sixth pumping cycles.

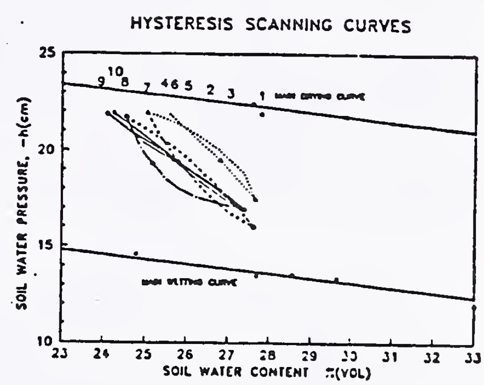

Figure 8. The last four pumping cycles (from points 6 through 10).

TITLE: PREFERENTIAL FLOW OF TRACER AND HERBICIDE UNDER FLOOD- AND SPRINKLER-IRRIGATED CONDITIONS

SPC: 1.3.02.1.a
1.1.02.1.c

CRIS WORK UNIT: 5422-20790-005

INTRODUCTION

Field experiments over the past several years have shown leaching rates of tracer and herbicide to greatly exceed mobilities expected based on water balance considerations (Bowman and Rice, 1986a,b; Rice et al., 1986; Annual Reports, 1983, 1984, and 1985). The water application method in these earlier studies was intermittent flood irrigation. Questions have arisen as to whether the observed preferential flow phenomena were at least in part a function of the irrigation method. Most (but not all) studies of solute movement under steady-state conditions have shown agreement between percolation rates measured with tracers and calculated from the water application rate and soil volumetric water content (Biggar and Nielsen, 1976; van de Pol et al., 1977; Jury et al., 1982). The experiment described below had two main objectives. The first objective was to compare directly the velocity of downward-percolating water under flood versus sprinkler irrigation. The second objective was to determine the magnitude of preferential flow effects in a very coarse-textured, unstructured soil.

MATERIALS AND METHODS

Experimental Site

The experiment was conducted on bare soil at the Yuma Mesa of the Yuma Agricultural Center of the University of Arizona. The soil at the site consists of a deep aolian sand which exhibits no evidence of soil structure. Eight experimental plots, four for sprinkler irrigation and four for flood irrigation, were established at the site (Fig. 1). The strips of land separating plots R1 and R2, and plots R3 and R4, were used for placement of the rainfall simulator which applied the sprinkler irrigations as described below. Plots F1 - F4, which received the flood irrigations, were separated from each other and from the surrounding soil by earthen berms constructed with a ditcher. Use of the ditcher, rather than a border disk, prevented the formation of a furrow along the inside peripheries of the berms.

Neutron probe access tubes were installed to a depth of 2.7 m in plots R2, R4, F2, and F4. A weather station was placed at the northeast corner of plot F3. Data were collected continuously on air temperature, relative humidity, windspeed, soil heat flux, soil surface temperature (by infrared thermometry), incoming solar radiation, and net solar radiation. Additional measurements of soil heat flux, soil surface temperature, and net radiation were collected by instrumentation situated in the northeast corner of plot R2.

After the experiment was completed, bulk density samples were taken in plots R1 and R3. A 1.8m deep trench was excavated with a backhoe in

each plot. Bulk density samples were taken from the pit faces at depth of 15, 45, 75, 105, 135, 165, and 180 cm. Vertical samples were taken in the floor of each pit in the 190 - 214 cm depth increment. Six samples (three from each pit) were taken at each depth. The bulk densities are presented in Table 1.

Tracer/Herbicide Application

Eight tracer/herbicide formulations were prepared. Each formulation contained 433 g KBr, 85.3 g of Hyvar-x (80% bromacil by weight), and 37.3 g of 85% KOH, in 16L of water. The KOH was added in order to increase the solubility of bromacil. A formulation was applied to each plot by making multiple passes with a hand-held spray rig.

Water Application

Table 2 presents the schedule of water applications. Water applications to plots F1 - F4 were via gated pipe placed along the west side of each plot. Application amounts were measured by an in-line flow meter. Water applications to plots R1 - R4 were via a rainfall simulator. The rainfall simulator was placed between plots R1 and R2, and plots R3 and R4; thus two plots were irrigated at the same time. The radius of the sprinkled area was 9 m. Application amount and uniformity was determined by eight catch-cans placed within the paired sprinkled plots. The application uniformity data is also presented in Table 2.

One of the goals of the sprinkler irrigation portion of the experiment was to avoid puddling of water on the soil surface and therefore the possibility of saturated flow conditions. This goal was not fully achieved. On March 7, the date of the first sprinkler irrigation, puddling of the soil surface began after 30-45 minutes. the 5-cm irrigation required about 3-hr sprinkling. For the subsequent irrigations, smaller sprinkler nozzles (20/100, rather than 30/100 used 7 March) were installed. With these smaller nozzles, puddling began 3 - 4 hours after sprinkling was initiated. A 7.5-cm irrigation required about 6 hrs. In no case was puddling severe enough to cause runoff.

The first six irrigations of 5-10cm of water, were applied at 1-2 week intervals on both sprinkler and flood plots. The last four irrigations of about 15 cm each were applied to the flood plots only.

Soil Sampling

Soil samples were taken on the dates indicated in Table 1. Samples collected on days 12, 18, 25, 32, 40, and 49 were taken in 30-cm increments using hand-driven Veihmeyer tubes equipped with 2.0-cm I. D. tips. Four samples were taken at randomly-selected locations in each plot on each date. On day 12, samples were taken to a depth of 1.8 m, while on the five later dates, samples were taken to a depth of 2.7 m.

Samples taken on day 243 were collected by making use of a trailer-mounted drilling rig. One sample was taken near the center of each flood plot. Samples were taken in 30-cm increments to a depth of 2.7 m using the Veihmeyer tube as described above. Below 2.7 m, samples were taken in 60-cm increments using the following procedure. An auger hole was drilled to the depth of the preceding sample, using a 7.5-cm O.D. screw auger. The auger was removed from the hole, care being taken to minimize fall-in of soil from shallower depths. A modified Veihmeyer tube, again with a 2.0-cm tip, was then driven 60 cm below the depth of the auger hole to collect an undisturbed sample. After removal from the bore hole, the soil sample was emptied onto a stainless steel tray and the loose, unconsolidated material at the top of the sample discarded. The undisturbed soil was placed in a Ziploc bag and put in an ice chest. Sampling continued in this manner to a depth of 10.0 m, where a water table was encountered. Samples were returned to the laboratory where they were frozen until analysis.

Chemical Analysis

For bromide analyses, a 20-g subsample of each core at field moisture content was extracted with 10 ml of water by shaking for 20 minutes in a 50-ml polypropylene centrifuge tube. After centrifugation and filtering, the bromide was quantified using an automated colorimetric technique adopted from Marti and Arozarena (1981). A separate 10-g subsample was taken at the same time for gravimetric moisture content determination. A final separate 10-g subsample was shaken with 10 ml of methanol for 20 minutes, for total extraction of bromacil. Bromacil content in the methanol extracts was measured via HPLC, using an octadecylsilane column and a methanol/water mobile phase, with ultraviolet detection at 280 nm.

RESULTS AND DISCUSSION

The depth of maximum Br^- concentration was determined for each site. The distribution of the Br^- peak depth from each sample period is shown in Figures 2 and 3 for the flood and sprinkle plots respectively. The normal distribution curve is also shown. There is considerably more variability on the flood plots than on the sprinkler plots. This would indicate that the infiltration rate was more uniform under sprinkler irrigation. The Br^- peak at day 49 was below the maximum sample depth for all holes under the sprinkler and 8 of the 16 holes under flood irrigation.

Bromide recovery was determined from sites where the complete tracer wave was recovered from the profile. The average recoveries were 102% for the sprinkler plots and 94% for the flood plots. The amount recovered varied between 17 and 570%.

The movement of Br^- downward through the profile is shown in Figure 4 for plot 4 under sprinkler irrigation and Figure 5 for plot 2 under

flood irrigation. The initial water content and water content at time of sampling is also shown. The depth-concentration curve is the average of 4 holes for that plot. The average was obtained by fitting the data from each hole to the one dimensional convection dispersion equation. The velocity and dispersion coefficients were averaged and the resulting fitted curve is shown. The concentration curve for days 40 and 49 under sprinkler and day 49 under flooding used the velocity and dispersion values from the previous time period. This was because of the large number of sites where the tracer peak had moved beyond the maximum sample depth. Under both irrigation regimes, the leading edges of the Br^- wave corresponds to the depth where the water content at sampling was the same as the initial water content. After day 25 on the sprinkle plots and day 32 on the flood plots, the water content at sampling was essentially constant.

The downward movement of the Br^- peak is shown in Figure 5 as a function of water applied. Each point is the average of 16 holes. The solute moved a little farther under sprinkler irrigation although the same amount of water was applied under each regime. Six irrigations were used on the sprinkler plots and 5 on the flood plots. The additional irrigation could have resulted in increased tracer movement.

The deep percolation was also determined from a water balance. Evaporation as calculated using the method described by Rice and Jackson (1985). The change in water storage was obtained from the neutron water content data. Dividing the deep percolation by the average water content and time, the water balance velocity was determined.

Table 3 summarizes the water balance data and average tracer velocity for the different times. There is no deep percolation from the water balance before day 32. The tracer velocities tend to increase with depth and, after day 40, were 7 and 6 cm/day for the sprinkler and flood plots respectively. The average water balance velocities for the same period were 3.6 and 3.2 cm/day respectively which is 1.9 times less than the tracer velocities. Preferential or bypass flow appears to be occurring in the sandy soil under both irrigation methods. The amount of bypass flow is a little less than was observed on a sandy loam soil where the differences in tracer and water balance velocities was 2.7. There appears to be no difference between the two irrigation methods.

Chemical analysis has been completed for bromide on the deep samples and bromacil on all samples but the data has not yet been analyzed.

SUMMARY AND CONCLUSIONS

Preferential flow of solute was observed on a sandy soil using flood and sprinkler irrigation methods. Solute velocities as determined from the movement of tracers was about 1.9 times faster than calculated using a water balance under both regimes. There was no difference in preferential flow between the two irrigation methods. The amount of bypass on

the coarse-textured, non-structured sand was about 67% less than measured on a sandy loam soil in previous years.

PERSONNEL

R. C. Rice, R. S. Bowman, J. B. Miller, and G. C. Auer

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Van de Pol, R. M., P. J. WIERENGA, and D. R. NIELSEN. 1977. Solute movement in a field soil. Soil Sci. Soc. Am. J. 41:10-13.

Table 1. Bulk density as a function of depth at the Yuma Agricultural Center field site.

Depth (cm)	Bulk Density (Kg/m^3) Mean	Std. Dev.
15	1.644	0.023
45	1.619	0.039
75	1.604	0.021
105	1.598	0.024
135	1.620	0.034
165	1.636	0.010
180	1.652	0.024
190 - 214	1.723	0.030

Table 2. Schedule of Irrigations, Irrigation Amounts, and Soil Sampling

1986 Date	Day	Soil Samples	F1	F2	F3	F4	R1 & R2[1]	R3 & R4[1]
7 March	0		9.32	6.43	7.95	7.65	4.84(0.62)	4.95(0.38)
19 March	12	X	-	-	-	-	5.16(0.93)	5.02(0.64)
25 March	18	X	8.74	11.23	10.11	10.03	7.43(0.67)	7.51(0.39)
1 April	25	X	7.62	7.62	7.62	7.62	7.33(0.47)	7.24(0.47)
8 April	32	X	6.60	6.60	7.62	5.59	6.95(0.55)	7.24(0.55)
16 April	40	X	7.57	7.49	6.12	8.13	7.60(0.41)	6.89(0.86)
25 April	49	X						
22 May	76		15.24	15.24	13.56	14.58		
24 June	109		15.14	15.60	15.95	15.82		
24 July	139		15.14	15.24	15.11	15.32		
26 Aug	172		15.44	15.24	16.33	14.58		
5 Nov	243	X						

[1] Numbers in parentheses are standard deviations.

Table 3. Infiltration, evaporation, storage, tracer velocity, water balance velocity and water content for sprinkler and flood plots.

	Sprinkler						Flood					
Day	I cm	EV cm	Storage cm	V_T cm/day	V_{WB}	θ m^3/m^3	I cm	EV cm	Storage cm	V_T cm/day	V_{WB}	θ m^3/m^3
0	4.96		20.94	–		.0790	7.8		21.7	–	–	.0835
		2.8						4.6				
12	5.1		23.45	3.75	–	.0902	0		24.1	3.4	–	.0927
		1.2						.6				
18	7.5		27.8	4.02	–	.1065	10.0		23.5	3.4	–	.0904
		1.8						1.8				
25	7.3		31.15	6.84	–	.1198	7.6		27.6	5.3	–	.1063
		2.8						2.6				
32	7.1		31.9	6.99	2.19	.1227	6.6		31.0	5.0	2.43	.1194
		2.8						3.4				
40	7.2		31.25	7.0	3.26	.1202	7.4		31.4	6.0	2.78	.1210
		2.9						2.3				
49	0		30.5	>6.0	3.93	.1173	0		31.1	>6.0	3.59	.1198
		39.1										

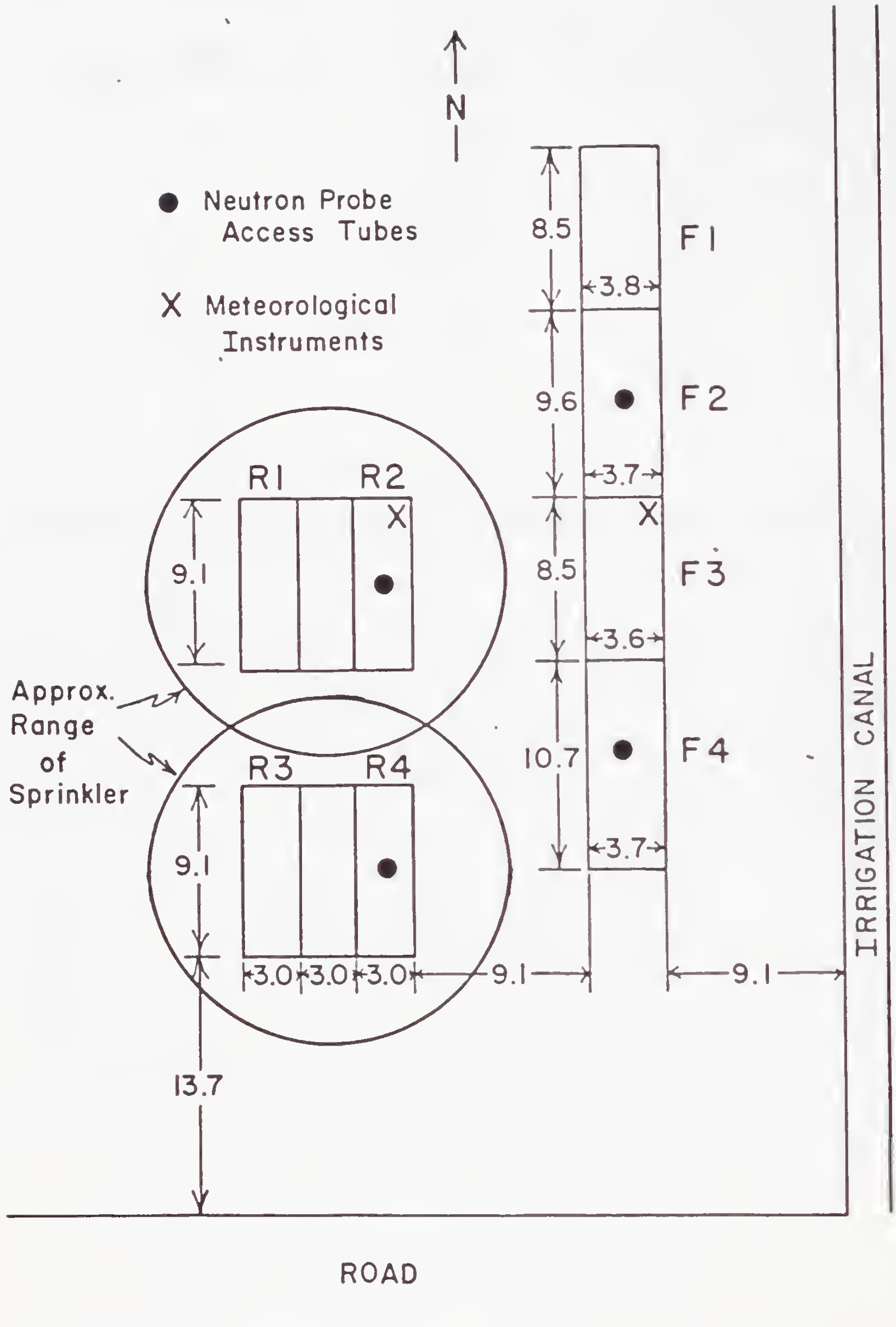

Figure 1. Schematic diagram of the field site. All dimensions in meters.

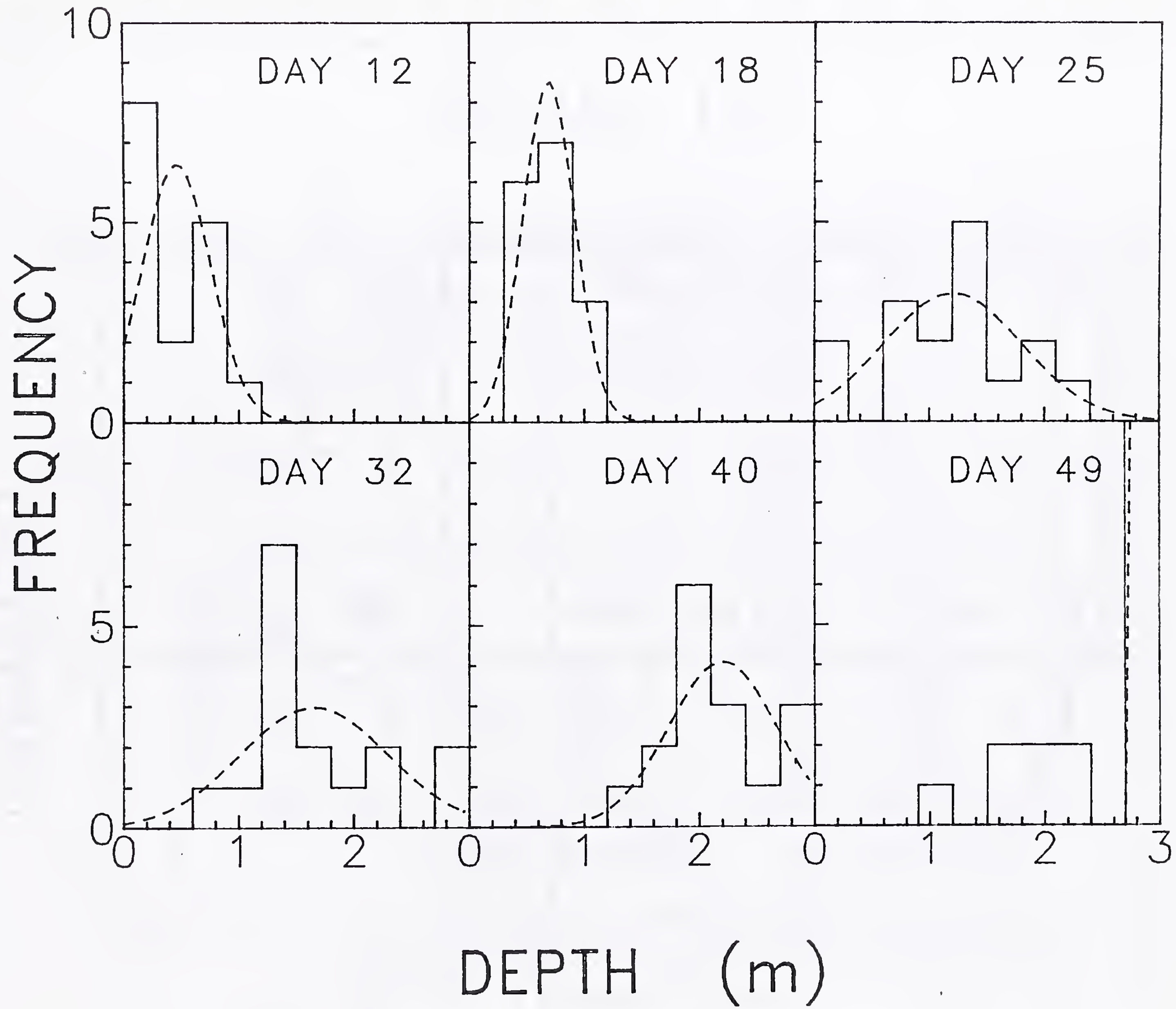

Figure 2. Histogram and normal distribution curve for depth of maximum Br^- concentration on flood plots.

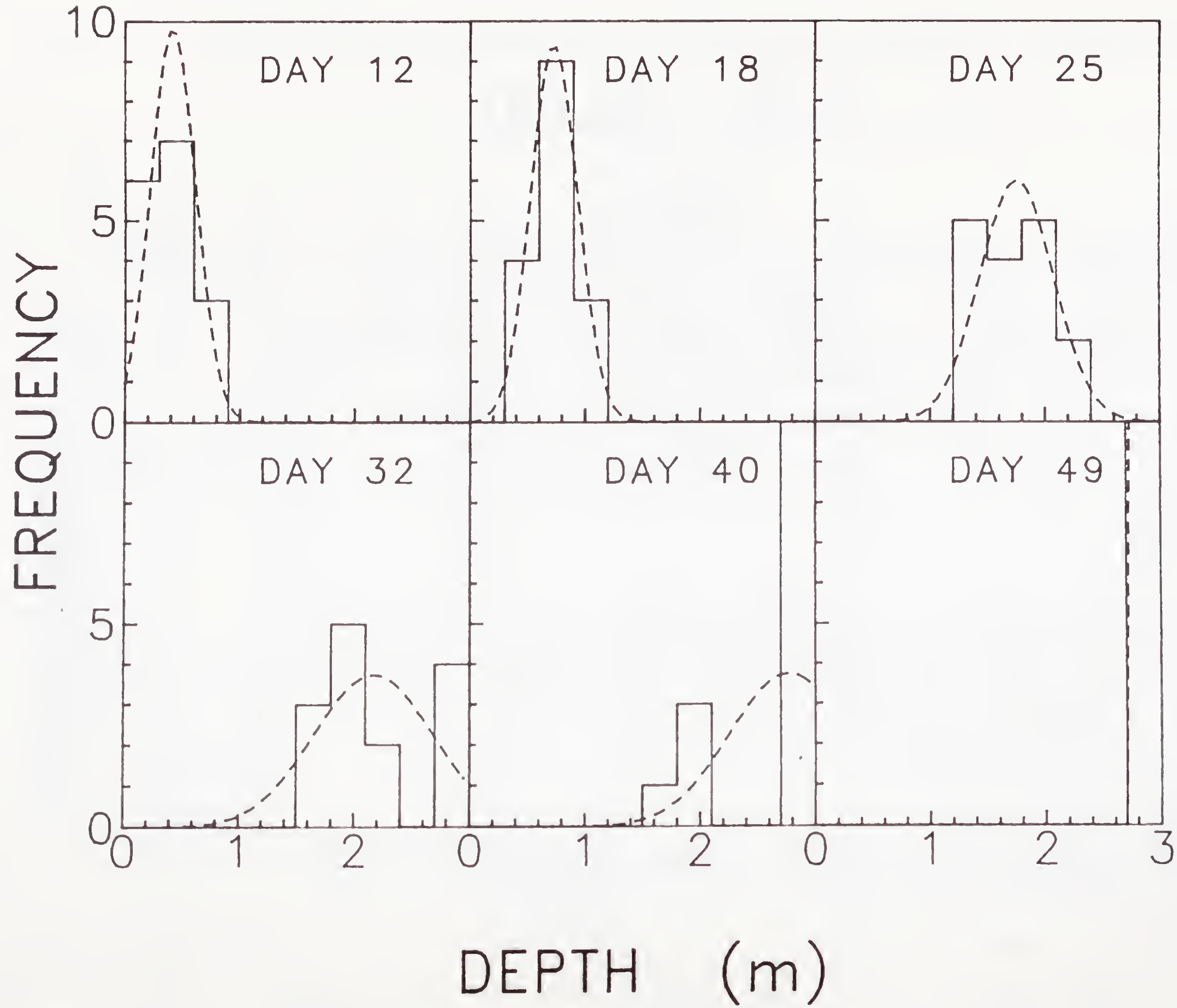

Figure 3. Histogram and normal distribution curve for depth of maximum Br^- concentration on sprinkler plots.

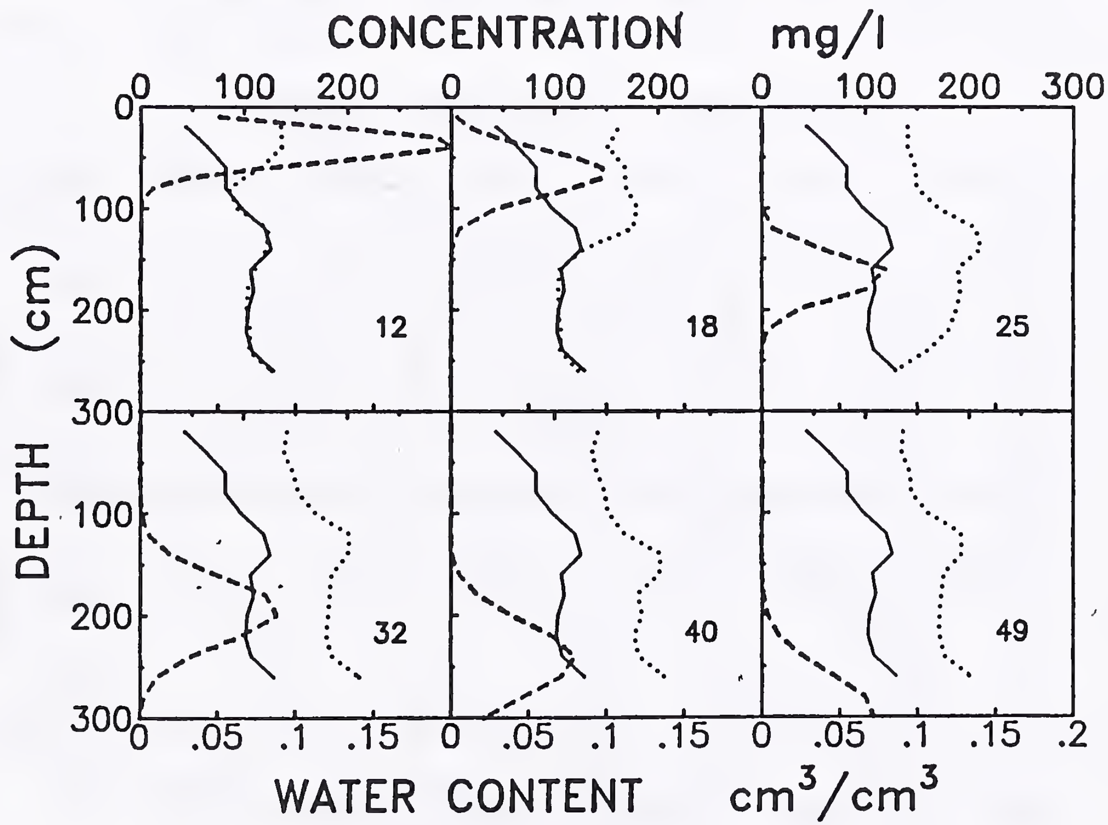

Figure 4. Water content and Br^- concentration with depth and time for plot 4 sprinkle plots. Solid line is initial water content; dotted line is water content at sample time and dashed line is concentration curve.

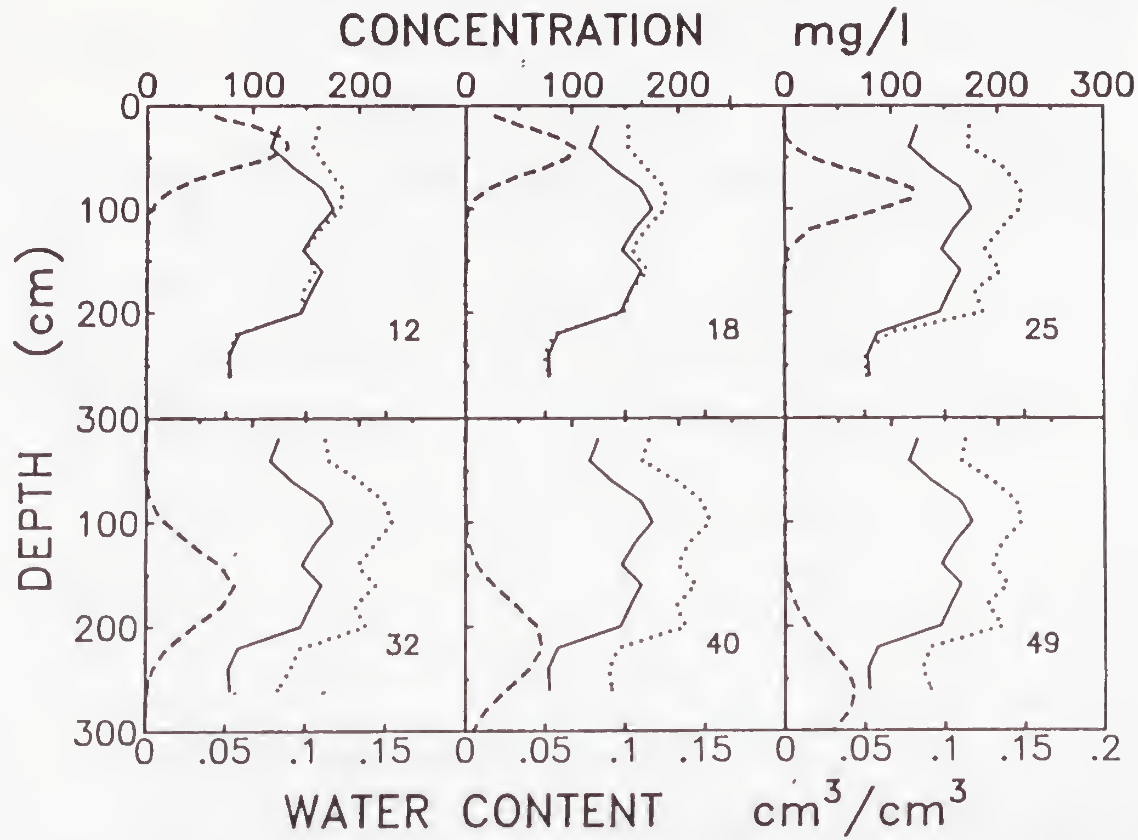

Figure 5. Water content and Br^- concentration with depth for plot 2 flood plots. Solid line is initial water content; dotted line is water content at sample time and dashed line is concentration curve.

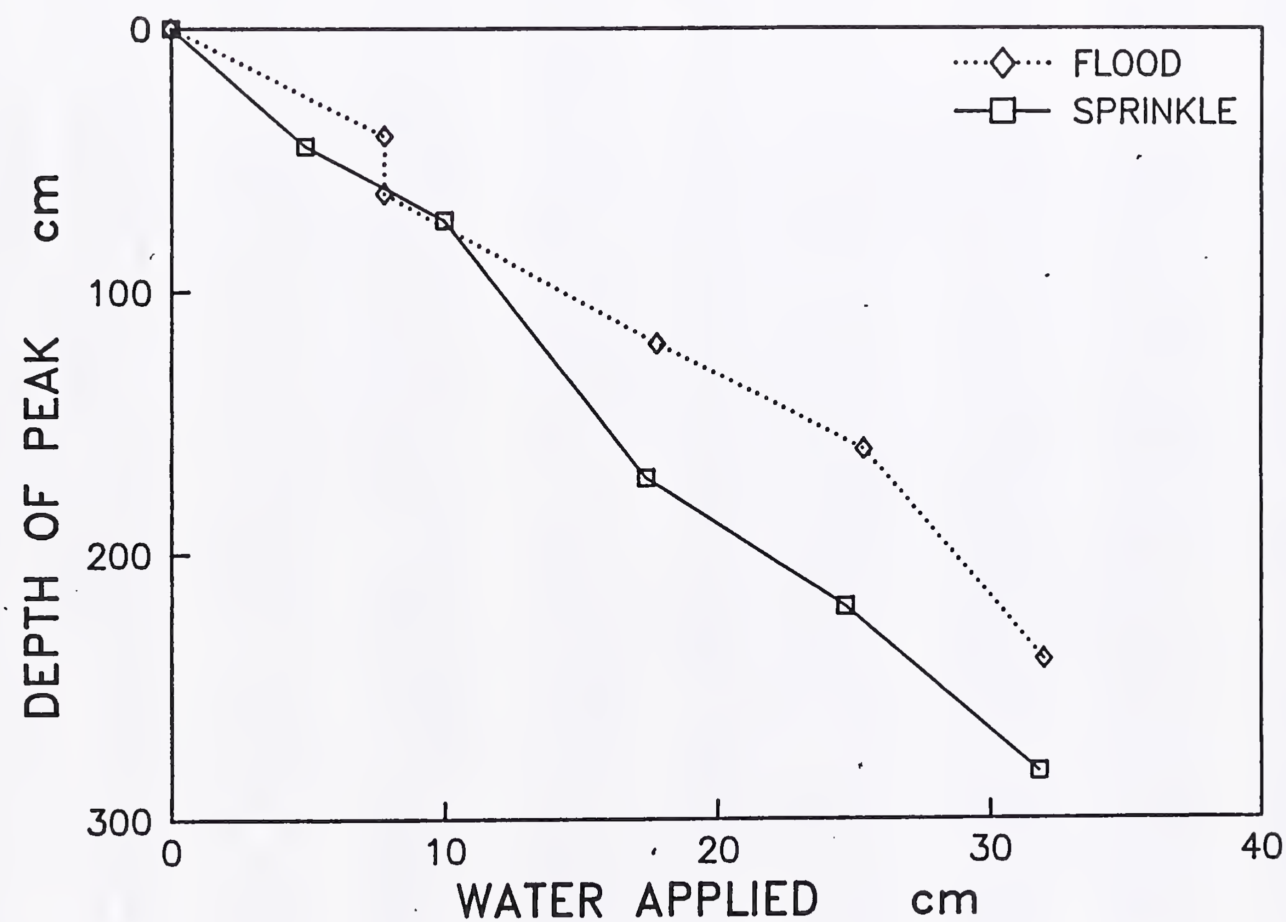

Figure 6. Average depth of maximum Br^- concentration with water applied for sprinkle and flood plots.

APPENDIX

LIST OF 1986 PUBLICATIONS AND MANUSCRIPTS PREPARED

ALEXANDER, W. L., BUCKS, D. A., and BACKHAUS, R. A. Irrigation water management for guar seed production. Agron. J. (in progress) (ms #1267)

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